DOCUMENT RESUME

ED 320 756 SE 051 232

AUTHOR	Vosniadou, Stella; Brewer, William F.
TITLE	The Concept of the Earth's Shape: A Study of Conceptual Change in Childhood. Technical Report No. 467.
INSTITUTION	Illinois Univ., Urbana. Center for the Study of Reading.
SPONS AGENCY	Office of Educational Research and Improvement (ED), Washington, DC.
PUB DATE	Apr 89
GRANT	OEG-0087-C1001
NOTE	75p.; Some drawings may not reproduce well.
PUB TYPE	Reports - Research/Technical (143)
EDRS PRICE	MF01/PC03 Plus Postage.
DESCRIPTORS	Cognitive Structures; *Concept Formation; *Earth Science; Elementary Education; *Elementary School Science; Fundamental Concepts; Gravity (Physics); *Misconceptions; Science Education; *Science History; *Scientific Concepts
IDENTIFIERS	*Conceptual Change Theory of Knowledge

ABSTRACT

This paper presents the results of an experiment which investigated elementary school children's concept of the earth's shape and the related concept of gravity. First, third, and fifth grade children were asked a series of factual, explanatory, and generative questions in an attempt to understand as clearly as possible the way they conceptualized the shape of the earth. An examination of the responses of individual children to these questions revealed inconsistencies. The inconsistencies could be explained by assuming that the children had formed and used in a consistent fashion various assimilatory concepts of the earth's shape; for example, that the earth is formed of discs, that there are two earths, one round and one flat, and that the earth is a sphere but people live on flat ground inside the sphere. This paper argues that children construct these assimilatory concepts in an effort to reconcile the information coming from adults that the earth is a sphere with their own naive concept of a flat earth. Changing these concepts will require a change of theory analogous in many respects to theory change in the history of science. (Author/YP)

CENTER FOR THE STUDY OF READING

Technical Report No. 467

THE CONCEPT OF THE EARTH'S SHAPE: A STUDY OF CONCEPTUAL CHANGE IN CHILDHOOD

Stella Vosniadou
University of Illinois at Urbana-Champaign and
Aristotelian University of Thessaloniki/Greece

William F. Brewer
University of Illinois at Urbana-Champaign

April 1989

University of Illinois at Urbana-Champaign
51 Gerty Drive
Champaign, Illinois 61820

The work upon which this publication was based was supported in part by the Office of Educational Research and Improvement under Cooperative Agreement No. OEG 0087-C1001, with the Reading Research and Education Center. The publication does not necessarily reflect the views of the agency supporting the research.

Abstract

This paper presents the results of an experiment which investigated elementary school children's concept of the earth's shape and the related concept of gravity. First, third, and fifth grade children were asked a series of factual, explanatory, and generative questions in an attempt to understand as clearly as possible the way they conceptualized the shape of the earth. An examination of the responses of individual children to these questions revealed considerable surface inconsistency. For example, many children said that the earth is round but at the same time stated that it has an edge and that people could fall down from that edge. A great deal of this apparent inconsistency could be explained by assuming that the children had formed and used in a consistent fashion various assimilatory concepts of the earth's shape, for example, that the earth is a disc, that there are two earths, one round and one flat, and that the earth is a sphere but people live on flat ground inside the sphere. We argue that children construct these assimilatory concepts in an effort to reconcile the information coming from adults that the earth is a sphere with a naive concept of a flat earth. We further interpret the presence of assimilatory models to support the hypothesis that children's concept of the earth is embedded within certain naive ontological and epistemological theories and that changing this concept requires a change of theory analogous in many respects to theory change in the history of science.

THE CONCEPT OF THE EARTH'S SHAPE: A STUDY OF CONCEPTUAL CHANGE IN CHILDHOOD

> A well-known scientist (some say it was Bertrand Russell) once gave a public lecture on astronomy. He described how the earth orbits around the sun and how the sun, in turn, orbits around the center of a vast collection of stars called our galaxy. At the end of the lecture, a little old lady at the back of the room got up and said: "What you have told us is rubbish. The world is really a flat plate supported on the back of a giant tortoise." The scientist gave a superior smile before replying, "What is the tortoise standing on?" "You're very clever, young man, very clever," said the old lady. "But it's turtles all the way down!" (S. Hawking, *A brief history of time*, 1988, p.1)

In most societies, the earliest conceptions about the earth were that it is flat, motionless, and that it is the center of the universe (Kuhn, 1957; Lambert, 1975; Toulmin & Goodfield, 1961). This leads to the possibility that young children may also initially adopt a flat earth position. It took science more than 2,000 years to settle on the current view of the earth as a sphere that spins on its axis and revolves around the sun. Thus, if children do adopt a flat earth position, they may also find it difficult to change from a flat earth to a spherical earth concept. The purpose of the study reported in this paper is to investigate children's concept of the earth's shape and to understand how this concept changes as children become exposed to the currently accepted model during the elementary school years.

The questions of how concepts are structured and how these structures change are fundamental for a theory of cognitive development. For a long time research about conceptual change was dominated by the view that concepts consist of necessary and sufficient features and that conceptual development is characterized by sequences of global representational shifts (i.e., stages). According to this view children start the knowledge acquisition process by forming concrete, instance-bound representations based on similarity to particular examples. Developments in children's logical capabilities allow them to move from these "pseudoconcepts" to form "real" concepts based on class inclusion and hierarchical classification (e.g., Bruner, Goodnow, & Austin, 1956; Piaget, 1962; Vygotsky, 1934/1986).

Criticisms of the Traditional View

Both the structural and developmental aspects of this theory of conceptual change have been severely criticized. We will focus here on two areas of criticism both of which have served to narrow the hypothesized differences between children and adults.

First, the notion that children go through sequences of stages has been attacked both on theoretical and empirical grounds (e.g., Carey, 1985; Fodor, 1972; Gelman & Gallistel, 1978; Mandler, 1983; Rozin, 1976). It has now become clear that, although preschool children may have difficulty with Piagetian class-inclusion tasks, they are able to form consistent and exhaustive classes from an early age in some cases (e.g., Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976; Ross, 1980; Sugarman, 1983). Some researchers have accounted for stage-like changes not in terms of global shifts but in terms of domain-specific shifts where the structure underlying particular stages may differ from one domain to another and where stage transitions may occur at different ages depending on the domain (e.g., Keil, 1986).

Serious problems have also been found with the notion that concepts are organized around necessary and sufficient features (Smith & Medin, 1981). Research has suggested that many concepts can be characterized only in terms of typical or characteristic features based on similarity to particular exemplars, regardless of whether they are formed by children or adults (e.g., Rosch & Mervis, 1975; Smith & Medin, 1981). However, in recent years researchers have become increasingly aware that similarity alone is not sufficient to provide an account of conceptional coherence and that concepts should not be viewed as consisting of a collection of independent attributes but of attributes embedded

in larger theoretical structures and as deriving their coherence and consistency from these theories (e.g., Medin, Wattenmaker, & Hampson, 1987; Murphy & Medin, 1985; see also the chapters on Similarity in Vosniadou & Ortony, in press).

Some of these same points have also been made by schema theorists (Brewer & Nakamura, 1984; Rumelhart, 1980). However, we will not use the schema framework and terminology in this paper because the term "schema" has frequently been associated with static knowledge representations which do not have the explanatory power of a theory (e.g., Abelson, 1981; Nelson, 1978).

The view that concepts are embedded in theories has found support in developmental psychology, cognitive science, and science education (e.g., Carey, 1985; Collins & Stevens, 1984; Driver & Easley, 1978; Keil, 1986; McCloskey, 1983; Osborne & Wittrock, 1983). For example, in her studies of the development of children's biological concepts such as "animal" and "living," Carey (1985) found that the younger children organized the properties of animals in a different way than the older children, but that even the youngest children in her sample (4-year-olds) showed evidence of using some biological knowledge to constrain their categorization. For example, the 4-year-old children said that a worm was more likely than a toy monkey to have a spleen (described as a green thing inside people) despite the fact that they thought that a toy monkey was more similar to people than a worm. The children showed in this way that they could differentiate surface similarity from category membership (see also Gelman & Markman, 1986; Vosniadou, in press; Vosniadou & Ortony, 1983).

Typically children's or novices' theories are rather different from the theories held by scientifically literate adults in our society and seem to be resistant to change. For example, in the domain of light many children believe that eyes perceive objects directly and that color is a property of the objects themselves (Anderson & Smith, 1986). Some novices in the area of electricity think that a switch is like the trigger of a gun. It sends an impulse to a battery to trigger current flow from the battery to a light bulb (Collins & Stevens, 1984). Sometimes novices' theories are found to resemble earlier theories in the history of science. For example, Clement (1982) and McCloskey (1983) argue that adult novices in mechanics hold a systematic conception of motion which bears a striking resemblance to a pre-Newtonian theory known as impetus theory. Brewer and Samarapungavan (in press) have also defended the position that children develop theories that share many properties of scientific theories.

Although the notion that concepts are embedded in theories has acquired increased acceptance (see Neisser, 1987), it has raised a whole new set of questions. What is the nature of these theories, where do they come from, and how do they change?

According to Keil (1986) children are born with certain structural constraints which allow them to induce theories (see also Keil & Kelly, 1986). Initially these theories consist of some skeletal but principled distinctions at the ontological level. Ontological knowledge becomes more differentiated and hierarchically integrated as children become older (see Keil, 1979; 1983). Similar approaches to the problem of conceptual change in terms of the increasing differentiation and hierarchical integration of existing structures are common in the expert/novice literature (e.g., Chi, Feltovich, & Glaser, 1981; Larkin, 1981).

Carey (1985; 1986) has called this type of conceptual change "weak restructuring" to distinguish it from a different kind of conceptual change which she calls "radical restructuring." According to Carey (1986) children start with two theories (e.g., an intuitive physics embodying physical causality and an intuitive psychology embodying intentional causality) from which new theories emerge, in ways analogous to radical theory change in the history of science (e.g., Hanson, 1958; Kuhn, 1970, 1977). This domain-specific radical restructuring is conceptualized either in terms of the separation of a new theoretical domain from a parent theory (e.g., the separation of biology from psychology), or in terms of theory change (e.g., the change from an impetus theory of motion to a Newtonian theory). In all of these cases, the new theory is different from the previous one in its structure, in the domain of the phenomena it explains, and in its individual concepts (Carey, 1985).

As we have discussed in an earlier paper (Vosniadou & Brewer, 1987), the distinction between weak and radical restructuring is an important one both because it captures the real difficulties students have in mastering some domains of knowledge (e.g., Newtonian mechanics), and because it has interesting theoretical implications for the areas of cognitive development and knowledge acquisition. The possibility of radical restructuring limits the number of concepts a theory of conceptual development must assume are innate and thus reduces some of the difficulty in understanding how children acquire new concepts (e.g., Fodor, 1980). The position that children begin with a few theory-like structures from which new, qualitatively different, knowledge structures emerge (Carey, 1985) depends crucially on the assumption that the process of knowledge acquisition is characterized by radical rather than weak restructurings. The notion of radical restructuring also raises important questions about the methods and content of instruction. It is possible that different methods of instruction are needed when the new knowledge to be taught requires a major restructuring of what is already known than when it does not.

The view that children's and novices' intuitive knowledge can be characterized as a theory and that conceptual change involves theory change is not without its critics. In a recent paper, diSessa (1988) has argued that intuitive physics is nothing but a fragmented collection of ideas which are loosely connected and do not have the systematicity that one attributes to a scientific theory. Solomon (1983) has made similar arguments. (See Brewer & Samarapungavan, in press, for a critique of this position.)

At present, many questions remain unanswered about the exact nature of the theories held by children or adult novices and the way these theories differ from scientific theories. Even if we assume that children have theories, there has not been convincing evidence so far that these theories become radically restructured in the course of development and knowledge acquisition. In order for these questions to be answered we need detailed descriptions of the knowledge acquisition process in a number of specific domains. The present study was undertaken in that context.

Theoretical Framework

Global and Domain-Specific Theories

In this section we will present a brief outline of our theoretical framework which will be described in greater detail in Vosniadou (in preparation). Central to this theoretical framework is a distinction between two kinds of "theories." As many philosophers of science have observed, the term "scientific theory" has been used to refer to at least two very different types of things: (a) a specific set of hypotheses or principles which can be utilized in making experimental predictions (such as Maxwell's theory of electromagnetism, Gallileo's theory of the tides, or Freud's theory of the unconscious) and (b) the much more fundamental, less easily testable sets of assumptions that have been referred to as paradigms (Kuhn, 1962), disciplinary matrix (Kuhn, 1970), ideals of natural order (Toulmin, 1961), collective ideals (Toulmin, 1972), research programs (Lakatos, 1970) and research traditions (Laudan, 1977). In the second, more fundamental use the term scientific theory refers to an entire family of doctrines (such as the theory of evolution or the atomic theory), which include common ontological assumptions and criteria for what constitutes a scientific theory.

When it comes to characterizing children's or novices' conceptual knowledge we propose drawing a distinction between "domain-specific theories" and "global theories" that is analogous, in some respects, to the one made in the philosophy of science. Both global and domain-specific theories embody a set of interrelated concepts that can explain a certain class of phenomena. The two kinds of theories differ, however, both in their generality and in their relation to each other. Global theories are more general than domain-specific theories in that they can generate hypotheses which can apply to many domains of enquiry, while domain-specific theories can explain only a limited class of phenomena. In addition, domain-specific theories are embedded within the global theories which constrain them. Concepts are embedded within both global and domain-specific theories.

The term "domain" is used roughly to refer to the various scientific disciplines as currently understood (e.g., physics, biology, economics, psychology, etc.). As conceptual knowledge becomes more complex, domains can be divided into subdomains and individual concepts can be elevated to domain theories. The notion we want to convey here is that of a hierarchy of nested structures from the more general (global theories) to the more simple (concepts).

Conceptual Change

We assume that children start the knowledge acquisition process with one or few global theories consisting of a set of core concepts and a notion of causality (see Miller & Johnson-Laird, 1976) which form the basis of their ontology and epistemology (their beliefs in the kinds of things that exist and in the nature of knowledge). Domain-specific theories emerge out of these global theories but are not limited by them. The development of a domain-specific theory can have implications which may cause the eventual restructuring of a global theory.

Conceptual change is assumed to involve both "weak" and "radical" restructurings. In most cases, individuals use information from observation or instruction to enrich existing conceptual structures. Occasionally, they may be faced with major anomalies that require radical theory changes. In this paper we will use the term "theory articulation" to refer to the kinds of changes that require the differentiation or hierarchical integration of existing structures (i.e., "weak" restructuring), and the term "theory restructuring" to refer to changes in explanatory framework (i.e., as "radical" restructuring). Theory articulation and restructuring can occur both at the level of domain-specific and global theories.

Theory Restructuring

Following Carey (1985) and her colleagues (Wiser & Carey, 1983) we assume that theory restructuring involves the replacement of a theory with a new theory different from the old one: (a) in its structure, (b) in its individual concepts, and (c) in the domain of phenomena it explains. In addition, radical restructuring at the level of a domain-specific theory usually involves the rejection of some fundamental beliefs associated with the global theory.

The rejection of deep beliefs associated with a global theory is a common characteristic of theory restructuring in the history of science. Revolutionary changes in the history of science have frequently involved the rejection of some fundamental beliefs dictated by the scientific paradigm or research program within which a domain-specific theory was conceptualized. For example, the Copernican revolution required giving up the belief that the earth stood in the center of the universe. Kepler's theory of planetary mechanics was based on the rejection of the belief that circular motion was the most perfect kind of motion. Newton's theory required the rejection of the belief in a static universe (e.g., Berry, 1961; Toulmin & Goodfield, 1961). Fundamental beliefs of that kind form the background assumptions within which scientific investigations take place and are very hard to change because they are not easily subjected to empirical testing. We think that the radical restructuring of an individual's structures can be conceptualized in a similar way. That is, as a conceptual change which involves the rejection of some of the individual's fundamental ontological and epistemological beliefs which constrain domain-specific theories and concepts. These types of changes can bring about the eventual restructuring of a global theory.

Theory restructuring at the level of a global theory requires replacing a global theory with a new one. This type of theory change requires the rejection of most of the fundamental assumptions of the old global theory. The restructuring of a global theory can affect more than one domain-specific theory in ways analogous to those described by Kuhn's (1962) paradigm shifts or Piaget's (1929) stages. This type of theory restructuring is different, however, from Piaget's stages because it does not derive from changes in the child's logical machinery, but from the adoption of a new explanatory framework.

Concepts, domain specific theories, and global theories constitute the structural component of a theory of conceptual change. This structural component needs to be distinguished from a procedural component which specifies how conceptual knowledge is used to solve problems, answer questions, or understand text. Fundamental to our view of how the human conceptual system operates is the construct of the mental model (Gentner & Stevens, 1983; Johnson-Laird, 1983). The term mental model has been used in a number of different ways (e.g., Brewer, 1987). The term is used here to refer to a particular mental representation constructed to deal with a specific problem. This form of representation differs from other types of mental representations in that its structure is assumed to "be identical to the structure of the states of affairs (perceived or conceived) that it represent. (Johnson-Laird, 1983, p. 419).

Mental models are assumed to be synthetic and dynamic structures which are generated from people's concepts and reflect the global and domain-specific theories within which these concepts are embedded. In the early stages of knowledge acquisition individuals have not yet constructed theories specific to different domains. Their concepts are embedded within global theories and the mental models they use are constructed out of these global theories. In the process of knowledge acquisition domain-specific theories emerge out of global theories and become continuously articulated and/or restructured. Domain-specific theories affect the structure of the individual concepts which comprise them and as a result give rise to different mental models during problem solving. For that reason, understanding the mental models individuals use to answer questions or solve problems can provide important information about underlying conceptual structure.

In this paper we explore the implications of this theoretical framework in a study of the development of children's concept of the earth's shape and the related notion of gravity. This study was undertaken in the context of a larger project investigating knowledge acquisition in the domain of observational astronomy. The purpose of the project is to understand the nature of children's initial conceptual knowledge about the earth, sun, moon and stars and to understand how this knowledge changes with exposure to the Copernican model during the elementary school years.

The Domain of Observational Astronomy

The domain of observational astronomy was chosen because it is a relatively rich domain composed of a number of concepts and their interconnections. It is therefore a domain where there is the potential for developing rich domain-specific theories. In addition to its richness, many of the phenomena which a theory of observational astronomy accounts for (e.g., the shape, size, movement, and position of the earth, sun and the moon, the day/night cycle, the phases of the moon, etc.) are accessible to young children. In other words, children's everyday experience provides them with enough information for constructing an intuitive understanding of such phenomena. Finally, the domain of astronomy has undergone a number of restructurings in its historical development (Kuhn, 1957, 1970; Toulmin & Goodfield, 1961). We thought that by selecting a domain which has undergone radical restructuring in its historical development we maximized our chances of finding similar restructurings in children acquiring knowledge in this domain.

The concept of the earth's shape is a core concept in a theory of astronomy and has been associated with a number of revolutions in the history of this science. The earliest conceptions about the earth were that it is flat and that it stands in the center of the universe. The earth was hypothesized to be flat in early Egypt (Kuhn, 1957; Plumley, 1985) in Sumeria (Lambert, 1975), in early Greece (Toulmin & Goodfield, 1961) and in early India (Gombrich, 1975).

In the historical development of cosmological theories the view that the earth is flat was eventually replaced by the view that it is a sphere. Aristotle in his book *On the heavens* offered a number of arguments as to why the earth should be a sphere. One of the arguments has to do with the position of the North Star. The Greeks knew from their travels that the North Star appears lower in the sky when viewed in the south than in the north, a change of location which is difficult to explain if we assume that

the earth is flat. Another argument was based on an explanation of the eclipses of the moon. Aristotle hypothesized that the eclipses of the moon were caused by the earth's shadow on the moon. Since this shadow was always round, he argued that the earth must be spherical.

The view that the earth is a sphere was fully elaborated by Ptolemy in his *Almagest*. According to Ptolemy, the earth was a sphere which stood motionless at the center of the universe. It was surrounded by eight spheres on which the sun, moon, five planets known at the time, and the stars were attached. The sun, moon and planets moved around the earth in orbits that were perfect circles. The stars were attached on the outermost sphere which also rotated around the earth with all the stars fixed on it. The Copernican revolution retained the view that the earth is a sphere but required a shift from a geocentric to a heliocentric universe and with it the rejection of the belief that the earth does not move.

In the present study we focused only on the changes in children's concept of the earth's shape. Changes in the concepts of the earth's motion, location, and size and the relationship of the earth with the sun, moon, stars and planets will be reported in later reports from our studies of knowledge acquisition in astronomy.

Children's Ideas About the Earth's Shape

We hypothesized that children, like the early astronomers, would start with the "common sense" view that the earth is flat, and that objects fall from up to down within this plane. This hypothesis was based on the observation that children share similar experiences with the early astronomers and because they are at a similar stage of theory formation, that is, they do not have a domain-specific theory of astronomy (McCloskey & Kargon, 1988).

Several studies of children's notions of the earth's shape (Nussbaum, 1979; Nussbaum & Novak, 1976; Sneider & Pulos, 1983) have confirmed this hypothesis. Although many children at this age say that the earth is round when asked, under more detailed questioning, ("Where does the sun go at night?" "What does the earth look like when you look at it from very far away?") give answers consistent with a flat earth view.

Unlike the early astronomers, children do not have to discover for themselves that the earth is a sphere. If we assume that children start with a flat earth concept, do they find it difficult to change to a round earth concept when they are told that the earth is a sphere?

The view of the earth as a sphere is counter-intuitive and contradicts a number of important ontological beliefs, such as the belief that the ground is flat and that things fall down. Indeed, the view that the earth is a sphere was often attacked by proponents of the flat earth view on the grounds that people on the other side of the spherical earth would fall off (Kuhn, 1957, p. 108). Because children lack the observational data which made it reasonable for the early astronomers to adopt the view that the earth is a sphere, it makes sense to assume that the information that the earth is a sphere would be difficult to understand.

There is some evidence which supports the hypothesis that the shift from a flat to a round earth concept is a difficult one to make and that in the process of making this shift children form various misconceptions regarding the earth's shape. For example, Nussbaum and Novak (1976) in an interview study of 26 second grade children discovered that children held five "notions" about the earth which differed in interesting ways from the adult scientific beliefs. Notion 1 included the children who said that the earth is round but answered all other questions as if they believed that the earth is really flat. Notion 2 was ascribed to the children who thought that the earth is round like a ball but lacked the idea of "unlimited space." These children thought that there is ground or ocean underneath the earth. The children who held Notion 3 lacked the idea of gravity. They believed that objects at the bottom of the earth would fall down into space. The children who held Notion 4 knew that objects at the bottom of

the earth do not fall in space but did not quite understand that gravity operates by pulling things toward the center of the earth. Finally, the children who held Notion 5 provided the accepted responses to the earth shape and gravity questions.

Nussbaum (1979) further tested the validity of these notions in a developmental study involving Israeli children. Five groups of 48 children from grades 4 to 8 were interviewed using a multiple-choice questionnaire on their earth shape and gravity concepts. The results suggested that Notions 1 and 2 should be combined and also uncovered a new notion, according to which the earth was like a huge ball consisting of two hemispheres: an upper hemisphere made up of "air" or "sky" and a lower hemisphere consisting of the ground where people live.

These results were further validated in a study by Sneider and Pulos (1983) in which 159 children from grades 3 through 8 were administered a structured interview based on a slight modification of the Nussbaum and Novak (1976) questionnaire. Sneider and Pulos concluded that most of the children in their sample who were below 10 years of age (grades 3 and 4) held Notions 1, 2, or 3, that most of the children aged 13 and over held Notions 4 and 5, and that the widest spread of notions was found among 11- and 12-year-olds.

Finally, Mali and Howe (1979) investigated the development of the earth shape and gravity concepts among Nepali children coming from both an urban and a rural region. They mention that in Nepal the traditional belief of adults who have had no schooling is that the Earth is a flat mass supported on four corners by an enormous elephant. However, the children are taught that the Earth is a sphere in the elementary school. Mali and Howe tested 250 children ages 8, 10 and 12 with tasks similar to those used by Nussbaum and Novak (1976). They report that the Nepali children showed earth shape concepts similar to the American children but that they tended to occur at later ages.

These studies raise difficult problems for a theory that assumes that "flat" is simply a feature of the concept earth. They also pose problems for a "weak restructuring" view to the problem of conceptual change (Chi, in press). Chi has argued that when new knowledge about a concept is introduced by adults in a school setting it is stored as a separate microstructure and is not related to the experientially derived knowledge about the same concept. These two microstructures remain unconnected and information from them is used to answer different kinds of questions. Such a model could indeed explain why children say that the earth is round when asked "What is the shape of the earth?" but answer the other questions as if they believed that the earth is flat. It cannot, however, account for the various alternate views regarding the earth's shape discovered by the empirical research just reviewed.

In our view, such alternate views reveal children's attempts to assimilate the information that the earth is round coming from adults to the information that the earth is flat coming out of their ontological theories. Piaget (1929, p. 236) reports an interesting case of such an assimilatory concept formed by a child attempting to understand the explanation of the day/night cycle. This child had been given an explanation of the day/night cycle in terms of the rotation of the earth; she had been told that when it was night in Europe it was day in America. The child assimilated this information into her existing concept by constructing a "layer cake" mental model of the earth. She developed a view that there was a flat earth America under the flat earth Europe and that at night the sun dropped through the European layer and illuminated the lower American layer. Notice that by constructing this view the child succeeded in retaining both her belief that the earth is flat and the information given by adults that when it is night in Europe it is day in America. Similarly, when children construct the view that the earth is composed of two hemispheres and argue that people live on the flat top of the lower hemisphere they succeed in retaining their belief that the ground is flat while they also incorporate the adult view that the earth is round.

Still it is possible that assimilatory concepts of this sort represent transitory attempts to provide solutions to new problems which the children have not encountered before. If this is the case then the alternate views should be ephemeral, unsystematic, and highly influenced by the nature of the specific

problem to which children or novices are exposed. However, if children's alternative conceptions about the earth have their roots in children's ontological theories we should find that they are robust, systematic, that they are used in more than one situation, and that they are difficult to change.

The empirical studies reviewed above are provocative but have not provided us with information regarding the systematicity, consistency, and robustness of children's misconceptions about the earth's shape. In many cases they did not even provide a description of the criteria used to identify children's "notions." In the present experiment we wanted to find out the kinds of mental models of the earth that children form to answer our questions and to understand whether these models are used in a stable and consistent manner.

Methodological Issues

The basic methodology used in this study consisted of asking children questions, some of which required a verbal response (e.g., "What is above the earth?") and others which required the children to draw a picture (e.g., "Make a drawing of the earth so that its real shape shows"). Crucial for our approach was the distinction between *factual* and *generative* questions. Factual questions (e.g., "What is the shape of the earth?") provided information about children's exposure to theoretically important facts. Children could answer these questions by simply repeating the information they had obtained from adults. Generative questions (e.g., "Does the earth have an edge?") were designed to reveal the mental models children used to answer questions to which they had not been exposed previously. Children's responses to these questions revealed the extent to which the information that the earth is a sphere had been incorporated into their underlying conceptual structures. Consider, for example, the questions "If one were to walk for many days on a straight line would one ever reach the edge of the earth? Does the earth have an edge?" If the children had fully understood the information that the earth is a sphere they should be able to employ a spherical earth mental model and on the basis of that to conclude that the earth does not have an edge and that if someone walked for many days in a straight line, one would come back to where one started. If, however, the children had not incorporated the information that the earth is a sphere in their conceptual structures they should answer this question by forming a mental model of a flat earth. Based on that model they should conclude that the earth has an edge.

In using this methodology we tried to understand, first, the kinds of mental models children constructed to answer our individual questions, and, second, the extent to which these models derived from a consistent underlying concept. We then tried to use this information to draw inferences about the nature and development of children's conceptual knowledge. More specifically we explored the hypothesis that children's concept of the earth's shape is embedded within a global theory and that changes from a flat to a sphere earth concept can be characterized in terms of (radical) theory restructuring.

Method

Subjects

The subjects for this study were 60 children: 20 first graders, ranging in age from 6.4 to 7.5 years (mean age, 6.9); 20 third graders ranging in age from 9.3 to 10.3 years (mean age, 9.9); and 20 fifth graders ranging in age from 10.3 to 11.9 years (mean age, 11.0). The children attended an elementary school in a town in Illinois. They came from middle-class and lower middle-class backgrounds. Approximately half of the children were girls and half were boys.

Materials

Materials consisted of a 48-item questionnaire. The questionnaire was developed through extensive pilot work and was designed to provide information about children's knowledge of certain critical

concepts in the domain of astronomy. Only the questions investigating children's conceptions of the earth shape and the related notion of gravity will be discussed in this paper.

As mentioned earlier, the questionnaire contained *factual questions* and *generative questions*. In addition, some *explanation questions* were included (e.g., "Why did you say that the earth is round?"). These questions were designed to provide us with information about the explanatory framework within which children's conceptual knowledge was embedded.

Procedure

The children were seen individually in interviews which lasted between 30 to 45 min. The interview was audio-taped but the experimenters also made detailed notes of the children's responses. The scoring was done on the basis of both the transcribed data and the experimenters' notes.

Follow-up questions and confrontation questions were used throughout the interview when children's responses appeared to be ambiguous or inconsistent. In order to resolve ambiguous responses the experimenter occasionally asked children to show the earth's shape using play dough. Often, we asked additional questions at the end of the interview in an effort to obtain as accurate a picture of children's concept of the earth as possible.

Scoring

The scoring key contained a set of categories for each question that covered as best as possible the range of responses obtained. For example, for the question "Can you draw a picture of the earth?", the scoring key contained the following categories:

Don't Know; Circle; Rectangle; Circle within square frame;
Oval; Straight line but changes to circle after questioning;
Other; Missing Data.

The category "Other" was devised to characterize responses which were meaningful but unique and could not be grouped under an existing category. The scores on each question were assigned independently of information taken from the other questions. It is important to emphasize that we did not try to interpret children's responses in the light of what we thought was their overall concept of the earth (as this concept was emerging during the questioning procedure) because we did not want to mask any possible inconsistencies or changes in the mental models they used to answer our individual questions.

After each response was classified, we checked to see the extent to which their individual responses could be generated by the consistent use of the same earth shape concept. On the basis of our empirical data as well as from previous research in this area we derived a number of possible concepts of the earth's shape and gravity. Then, for each question we generated the answers expected if the children had used one of these concepts. For example, if the children used a sphere earth concept consistently we expected them to say that the earth is round or spherical to Question 1, that you look down to see the earth to Question 3, that there is no edge to the earth to Question 15, to draw a circle to depict the earth in Question 11, and so on.

Once we derived the pattern of responses expected for each question for all concepts investigated, we were able to determine the degree of correspondence between the expected and obtained responses to the relevant questions. Children were assigned to a specific concept of the earth's shape if their responses had no more than one deviation from the expected pattern and only if this deviation occurred in a non-core item for that category. Children who appeared to use more than one concept to answer the questions were placed in a mixed concept category. If children's responses could not be explained by the use of one or more concepts, they were placed in a category called undetermined.

Notice that we have adopted a fai ly conservative criteria for classifying a child's concept of the earth. If a child was using a consistent model that we did not understand, our procedure would probably place the child's concept in the mixed or undetermined category. Information about the criteria used for assigning concepts to children will be discussed in greater detail in the results section.

The scoring key originally constructed was used by two independent judges to score half of the data. It was then modified in order to cover the full range of responses obtained. The data was rescored using this modified scoring key. Agreement between the two independent judges at the end of the scoring was generally high (94%). All disagreements were resolved after discussion.

Results

Earth Shape Concept

A total of 16 questions were asked in an effort to understand children's earth shape concept. The first part of this section gives the theoretically important item level data and the later sections give data on the children's concepts which were derived from the item data. The interview started with the question, "What is the shape of the earth?" This was a factual question designed to show whether the children had been exposed to the information that the earth is a sphere. The responses to this first question appear in Table 1. Most of the third (17 out of 20) and fifth grade children (18 out of 20) said that the earth is "round," but the majority of the first graders used the word "circle" to indicate the shape of the earth (14 out of 20 responses). It is not possible to determine from children's responses to this question alone whether the use of the term "circle" was related to a lexical difficulty (i.e., the children used "circle" to mean "round" because they did not know the word "round"), or to a conceptual confusion (i.e., they used the word "circle" because they thought that the earth is like a flat disc rather than a sphere), or to both. Even the word "round" is ambiguous with respect to whether it refers to a sphere or a disc. The unambiguous responses "sphere" or round like a ball" were used rarely (only in 5 out of 60 responses).

[Insert Table 1 about here.]

Question 3 (Table 2) asked the children, "Which way do we look to see the earth?" an item originally used by Nussbaum and Novak (1976). Many of the children (23/60) including the majority of the first graders (12/20) said that you look "up" to see the earth. We do not know why so many children gave this response. It is possible that they interpret looking out to the horizon as "looking up." This response could also be interpreted as evidence for a "dual earth" concept. According to the dual earth concept there are two earths: a flat one on which we live and a round one which is up in the sky.

[Insert Table 2 about here.]

Question 3 was followed up with the questions, "What is above the earth?", "What is below the earth?", and "What is to the sides of the earth?" The responses to those questions were not very informative. Most of the children said that "the sky" was above the earth, and that either "the sun or the moon" were to the sides of the earth.

When asked to draw a picture of the earth (Question 11; Table 3), most of the children drew a circle (54 out of 60). Again, because of the ambiguity of the shape represented by a drawn circle, it was not possible to determine from this response alone whether the children were attempting to draw a spherical earth or a disc earth. Two children drew an oval-like shape, while two others drew a straight line at first but then changed to a circle when asked if this is how the earth would look like if they were in a spacecraft. One child drew a circle and placed it in the middle of a square frame. Finally, one first grader drew a rectangle. This was the only clear evidence of a non-circular flat mental model of the earth's shape.

[Insert Table 3 about here.]

In the next question (Question 12, Table 4) the children were asked to add the moon, stars, and sky to their earth drawings. This item was designed to find out whether the children would place the solar objects and the sky all around the earth or whether they would be faithful to their experience and place them only above the earth. Quite a few of the children (24/60) drew the moon and stars above the circle. About an equal number (26/60) placed the solar objects on all sides of the circle. However, 8 of those (mostly first graders) drew a horizontal line to depict the sky, revealing in that respect the remnants of a naive concept of the earth. Finally, 8 children drew the moon and the stars inside the circle. Initially this may seem puzzling but when the children were asked about their drawing they stated that they meant to put the moon and stars *on top* of the circle, not inside it. These children seemed to view the circle as representing the flat top of a round earth (round like a disc or like a truncated sphere) with the moon and stars located directly above it.

[Insert Table 4 about here.]

The hypothesis that some children conceptualized the circle as the flat top of the earth was reinforced by their responses to Question 13 which asked them to show where the people live with respect to their earth drawing (Table 5). Practically all the children drew their people inside the circle (50 out of 60 responses), rather than on the perimeter of the circle where most adults draw them. Only two first grade children drew a person standing on the top part of the circle's perimeter. Three children drew their people on a straight line inside the circle giving some initial evidence for the belief that people live inside the earth. Three more children drew a person on a straight line outside the circle revealing their uncertainty as to whether people live on the sphere or not. Two of these children eventually changed their minds and put their people inside the circle. The child who drew the rectangle put his person inside the rectangle.

[Insert Table 5 about here.]

The children were also asked to show in their drawings where Champaign-Urbana and China (Question 19) are located. Most children (47 out of 60) indicated that both places were inside the circle. Some children said that China is on the other, non-visible, side of the earth, a response consistent with the belief that the earth is a sphere (9 out of 60). One child said that China is outside the circle, and another did not know where China was. The remaining 2 children did not know where to place Champaign-Urbana and China.

In the next question, the experimenter showed the children a picture of a farm house in the middle of a flat landscape and (if they had drawn a round earth) asked them to explain why "here the earth is flat but before you made it round." A few children (3 out of 60) did not know how to answer this question, others did not seem to recognize the flat/sphere conflict (Responses No. 2 & 4, in Table 6), while one child changed from a round to a flat earth response (Response No. 3). Here is the protocol of the child who changed from a round to a rectangular earth response.

[Insert Table 6 about here.]

Betsy (1st grade) [Response No. 3, change from round to rectangle]

E: How come here the earth is flat but before you made it round?
C: No response.
E: What's the real shape of the earth?
C: It's a circle.
E: How come it looks flat there?
C: It's a rectangle looking like that.
E: Yeah, so what's the real shape?

C: It's an oval . . . it's like a rectangle . . . no I mean (child points to her original rectangle shape). It's like that.
E: I think you used the right word. That is a rectangle.
C: Child nods.
E: So is it round or is it kind of flat?
C: Flat.

Some children (27 out of 60) recognized the flat/sphere conflict and tried to explain it (responses No. 10 & 11). These children said that the earth is really round but appears flat when you are on it, or that it appears flat because it is very big. Here are some characteristic responses:

Don (3rd grade) [Response No. 10, no explanation]
E: How come here the earth is flat but before you made it round?
C: The earth is actually moving around. It's flat, you know, like on some lands, but it is not actually. I don't quite know how to explain it, but it's actually round, but people can't tell. Unless they're up on the moon. It looks flat but it's actually round.

Isaac (3rd grade) [Response No. 11, explanation]
E: How come here the earth is flat but before you made it round?
C: Well, here it looks like the earth is flat, but just that where we're at it's so big, it looks flat.

Finally, a number of children gave responses indicating that they had an earth shape concept which was not spherical. Some children (4 out of 60) said that the earth is round like a thick pancake (disc), that people live inside the earth (14/60), that we live on flat pieces of land on the top of the earth (1/60), or that there are two earths: a flat one on which we live and a round one which is up in the sky (4/60). Here are examples of these response categories:

Brandy (1st grade) [Response No. 8, two earths]
E: How come the earth is flat but you made it round?
C: Because the earth is up in the sky and that's (house) down on the earth.

Terina (5th grade) [Response No. 5, disc]
C: The earth is round but when you look at it, it is flat.
E: Why is that?
C: Because if you were looking around it would be round.
E: But what is the real shape of the earth? Is it round like a ball or is it round like a thick pancake?
C: Round, like a thick pancake.

Matthew (1st grade) [Response No. 6, inside-the-sphere]
C: On the earth we have to have ground so we can plant trees and make houses and plant flowers and make gardens.
E: But how come it looks flat here and round in this picture?
C: Because inside the world we have a whole big kind of like universe and it's just all flat on the ground.
E: So is the earth round like a ball or is it sort of like a thick pancake?
C: It's round like a ball.
E: So where does the flat come in?
C: Inside, inside the countries.

Subsequently, the children were asked the questions, "If you walked and walked for many days in a straight line, where would you end up?"; "Would you ever reach the edge of the earth?" and the follow-up question, "Is there an edge to the earth?" and "Could you fall off the edge of the earth?" The first three questions were scored together in order to distinguish the children who thought that there is an edge to the earth but it cannot be reached (because it is too far away, or there are oceans or high mountains in between, etc.) from those who thought that there is no edge to the earth. The responses to these questions appear in Tables 7 and 8.

[Insert Tables 7 & 8 about here.]

As Table 7 shows, 38 out of the 60 children said that the earth does not have an edge. Of these, only 22 were able to justify their responses. Here is an example of a justified response.

Charles (3rd grade) [Response No. 4 - no edge-justified]

E: If you walked for many days in a straight line, where would you end up?
C: On the other side of the earth. You'd come around to the side you were on before. You'd go on the other side.
E: Would you ever reach the edge of the earth?
C: No.

Fourteen children (10 first graders) thought that there is an edge to the earth and said that people could fall down from that edge (Responses No. 3, 4, Table 8). Here is an example of that type of response:

Kristi (1st grade) [Response No. 3 - fall off]

E: If you walked and walked for many days in a straight line, where would you end up?
C: You would end up in a different town.
E: Well, what if you kept on walking and walking?
C: In a bunch of different towns, states and then, if you were here and you kept on walking here (child shows edge of circle), you walk right out of the earth.
E: You'd walk right out of the earth? huh?
C: Yeah, because you just go that way and you reach the edge and you gotta be kinda careful.
E: Could you fall off the edge of the earth?
C: Yes, if you were playing on the edge of it.
E: Where would you fall?
C: You'd fall on this edge if you were playing here. And you fall down on other planets.
E: Down on other planets?
C: Yes. You could land on Mars. Like if you were on a spaceship, you would go out this way and if you crashed you would be on Mars.

Apparently children like Kristi must have thought that the earth is flat on the top (like a disc or a truncated sphere) and that it had an edge from which people could potentially fall off. Some children clearly thought there was an edge to the earth but were reluctant to say that they would fall off because they would try to hold on to the edge of the earth real tight!

Renae (1st Grade) [Response No. 3, fall off]

E: Could you ever reach the edge of the earth?
C: Yes.
E: Could you fall off the edge of the earth?
C: No.

E: Why not?
C: Because once you fall off, you can't get back on.
E: Well, would you ever fall through?
C: No.
E: What if you could get back on, do you think you could fall off then?
C: Yes . . . and if you took the edge of the thing, and you had one hand on it, you could fall off easier.
E: So if you were hanging on the edge it would be easier to slip off, is that it?
C: Yea, but you can't hold on . . . and if you were holding on to both hands and you couldn't hold on and you tried to pull yourself back on and you had your pinky on it and you couldn't hold on much longer, all you have to do is to hold the whole hand on it.

A few children believed that there is an edge to the earth but that people are inside the earth and therefore they cannot reach that edge or if they reach it they cannot fall off of it. Here is an example of this response.

Matthew (1st grade) [Response No. 6, inside-the-sphere]
E: If you walked and walked for many days in a straight line where would you end up?
C: If we walked for a very long time we might end up at the end of the earth.
E: Would you ever reach the edge of the earth?
C: I don't think so.
E: Say we just kept walking and walking and we had plenty of food with us.
C: Probably.
E: Could you fall off the edge of the earth?
C: No. Because if we were outside of the earth we could probably fall off, but if we were inside the earth we couldn't fall off.
E: You'd be walking inside the earth?
C: Yeah, I'd be walking on the countries.
E: Would you ever reach the edge of the earth?
C: If I had a rocket I could.
E: Is there an edge to the earth?
C: Yes.
E: So could you reach it if you walked long enough?
C: Well, if I walked and walked, let's say there is a space port down here, and I just walked for days and days and days, I would get to the space port and I'd probably get trained like for a rocket and I could probably reach that edge with a rocket if I blasted off.
E: Could you walk to the edge of the earth?
C: No.
E: How come you can't walk to it, but you can take a spaceship to it?
C: Like if you went up in space and then you were going to come back down you would reach the edge.
E: But if you were walking on the earth, could you reach the edge?
C: No, because you can't walk up in space.
E: So is there an edge to the earth?
C: Yes.
E: Can we walk over to the edge and just stand there and look?
C: Well, we can walk to a dead end.
E: What if we took one more step?
C: Well, if there was construction, you would fall into a hole.

Matthew seems to think that we are at the bottom of a hollow sphere, and that we cannot reach the edge of the earth unless we take a spaceship.

Finally, two children believed that there is an edge to the earth but that you cannot fall off it because gravity will hold you down.

The last question designed to investigate the earth shape concept was Question 20, "Tell me in this picture what is down here below the earth?" Most children mentioned the sky, the clouds or solar objects. The older children were much more likely to use the word "space" than the younger children (1/20, 5/20, and 8/20 for first, third and fifth grade respectively). Finally, a few of the first graders said that there is "dirt," "ground," "grass," or "us" below the earth (6 out of 20 first grade children), indicating that they possibly had a dual earth model.

[Insert Table 9 about here.]

Children's Concepts of the Earth's Shape

Children's responses to our individual questions revealed tremendous surface inconsistency. The same child would say that the earth is round, a response consistent with a spherical concept, and yet answer the question regarding the edge of the earth as if he or she believed that the earth is flat. These inconsistencies became more pronounced when we compared responses to the factual versus the generative questions. For example, 99% of the children said that the shape of the earth is either a circle or round, but only 63% of those said that the earth does not have an end. And, while 94% of the children drew a circle to indicate the shape of the earth, 38% said that you look "up" to see the earth. These discrepancies showed that many children who had been exposed to the information that the earth is a sphere were not able to understand this information in the way that the adults intended it.

Inconsistencies were not only observed between responses in the factual versus generative questions. There were important discrepancies among children's responses to the different generative questions themselves. For example, only 23% of the children's responses to the question about the earth's edge were consistent with a spherical earth concept as compared to 45% spherical earth responses to the question "What is down here below the earth?" (i.e., they said that there is sky, space or solar objects below the earth).

Were the children truly inconsistent or could the apparent inconsistencies be explained by assuming that children had constructed an alternate concept of the earth?

In order to find out whether children's seemingly inconsistent responses were internally consistent with respect to these alternate concepts we devised the following methodology. For each identified alternate earth shape concept (sphere, questionable sphere, inside the sphere, disk, dual earth, flat) we generated the pattern of responses expected if the child had used that concept consistently. For example, we assumed that if the children had used a consistent disc earth concept they would say that the earth's shape is round or a circle, that you look down to see the earth, and that there is an edge to the earth. These children should draw a circle to depict the earth and they should put the people, Urbana-Champaign, and China inside the circle. They should be more likely than the sphere children to place the moon and stars inside or on top of the circle and to say that there is ground or water below it.

Once the pattern of responses for each earth shape concept was generated, it was used to determine the degree of correspondence between the expected and obtained responses to the relevant earth shape questions. The criteria for assigning children to a given concept were that they show no more than one deviation from the expected pattern and that this deviation does not occur in the case of the "core" items for that category. Core items were the items whose deviation could not be explained without assuming that the children had formed a mental model which was inconsistent with the assumed earth shape concept. Take, for example, the response "circle" to the question "What is the shape of the earth?" This response could be given by a child who had formed a spherical earth mental model but

who either did not know the word "sphere" or "round," or thought that the word "circle" means round. This item could not therefore be a core item for the spherical earth concept. On the other hand, an affirmative response to the question about the earth's edge raised significant doubts about whether a child had a stable spherical earth concept, because it could not have been generated by a spherical earth model. This item was therefore considered a "core" item for the spherical earth concept.

More information about the criteria adopted for placing children in the various earth shape concepts and about the core items in each category is presented in Table 10 and will be discussed in greater detail below. The following earth shape concepts were postulated and appear to have been used in a consistent fashion by some of the children in our sample.

[Insert Table 10 about here.]

Sphere concept. Children were placed in this category if, and only if, they gave the pattern of responses described in Table 10. More specifically we expected the children who made consistent use of a sphere concept to say that the Earth is either "round" or "sphere" (Question 1), that we look "down," "sideways" or "all around" to see the earth (Question 3), to draw a circle to indicate the earth's shape (Question 11), to place the stars and the moon either above or all around their earth drawing and to say that the sky is everywhere (Question 12), to draw the people (Question 13) and China and Urbana (Question 19) inside the circle, or to indicate that China is on the other side of the spherical earth, to understand and try to explain the flat/sphere conflict, although a complete explanation was not deemed necessary (Question 14), to state that there is no end/edge to the earth because the earth is round and therefore you come back to where you started (Questions 15/16), and finally to say that below the earth is space or solar objects (Question 20).

All the children placed in the sphere concept category had this pattern of responses. The only deviations occurred in Questions 1 and 3 which were not considered to be core items for this category. More specifically, one child said "circle" to Question 1 instead of "round" or "sphere," and three children said "up" instead of "down" to Question 3.

The following is a typical example of a child with a sphere concept.

Ethan (1st Grade)

E: What is the shape of the Earth?
C: It's the shape of a ball.
E: Which way do we look to see the Earth?
C: Down.
E: What is above the Earth?
C: Space.
E: What is below the Earth?
C: Space.
E: Can you draw a picture of the Earth?
(The child draws the picture shown in Figure 1.)

[Insert Figure 1 about here.]

E: Show me where the moon and stars go.
C: Well, the stars go all around it, and the moon could probably be up here. And here could be the sun.
E: Now draw the sky.
C: The sky has no shape. You mean space. I can draw the sky around the Earth.
E: How come here the earth is flat but before you made it round? (The child is shown the picture of the farm house on what appears to be a flat Earth.)

C: Well the earth is so big it looks flat but it's round. If it's round and it's huge, people see it as flat. I think the islands are flat, I think. I think the islands are a bit curved but people don't notice it.
E: If you walked and walked for many days in a straight line, where would you end up?
C: Back where you started.
E: Would you ever reach the edge of the earth?
C: No, because gravity pulls you down.
E: Is there an edge to the earth?
C: No.

Inside-the-sphere concept. This category included children who seemed to use one of two types of mental models: One was the mental model of a hollow sphere, and the other the mental model originally identified by Nussbaum (1978) that the earth consists of two hemispheres; a lower hemisphere on which people live and an upper hemisphere which consists of the sky covering the lower hemisphere like a dome. It was not possible to always distinguish these two mental models from each other. The pattern of expected responses for this concept appears in Table 10 and the individual responses of the 10 children who met the criteria for placement in this category appear in Table 11.

[Insert Table 11 about here.]

All the children placed in this category said, on more than one response, that the earth is a sphere and that we live inside it. One core item for placement in this category was the explanation of the flat/sphere conflict in Question 14 from the point of view of an inside-the-sphere concept. All the children in this category said that the earth looks round from the outside (i.e., from space) but it looks flat to us because we are inside the earth. Another core item for this category was the response to Question 15/16 about the end/edge of the earth. In response to this question, some children said that there is an edge to the earth but it is on top of us and we cannot reach it, revealing a hollow earth model. Other children said that there is no edge to the earth. These children apparently thought of the earth as a circular surface enclosed at the edges by the sky and therefore without a true edge.

The children placed in this category gave a number of other responses consistent with the inside-the-sphere concept. Five out of the 10 children in this category drew the stars and moon inside the circle (Question 12), 3 drew the people on a flat line inside the circle (Question 13), and 5 said that the earth is all around us when asked "Which way do we look to see the earth?" (Question 3). This response was very rare in the children assigned to the other earth shape concepts. The only responses that were inconsistent with the inside-the-sphere concept were the response "ground" to Question 20, "What is here below the earth?" which was given by 2 children, and the response "circle" to Question 1, "What is the shape of the earth?" which was given by 3 children.

Here is a typical example from the inside-the-sphere concept.

Veronica (3rd Grade)

Veronica drew the picture of the Earth shown in Figure 2.

[Insert Figure 2 about here.]

E: How come here the earth is flat but before you made it round?
C: Because you are on the ground and you make that picture like a shape and you made it a square shape and if you'll look up it'll look like a rectangle or something like that and if you go out of earth and go into space you'll see a circle or round.
E: So what is the real shape of the earth?
C: Round.

E: Why does it look flat?
C: Because you are inside the earth.
E: If you walked and walked for many days in a straight line, where would you end up?
C: Somewhere in the desert.
E: What if you kept walking?
C: You can go to states and cities.
E: What if you kept on walking?
C: No response.
E: Would you ever reach the edge of the earth?
C: No. You would have to be in a spaceship if you're going to go to the end of the earth.
E: Is there an edge to the earth?
C: No. Only if you go up.
E: Does anyone live here on the bottom of the Earth?
C: No, because they live in the states up here.
E: But could they live down here?
C: Yes.
E: Why wouldn't they fall off?
C: Because they are inside the Earth?
E: What do you mean inside.
C: They don't fall, they have sidewalks, things down like on the bottom.
E: Is the earth round like a ball or round like a thick pancake?
C: Round like a ball.
E: When you say that they live inside the earth, do you mean they live inside the ball?
C: Inside the ball. In the middle of it.

Disk concept. The pattern of expected responses for the disc concept is shown in Table 10. The core items for placement in this concept were the following: (a) child draws a circle to depict the earth in Question 11, (b) explains the flat/sphere conflict in Question 14 by saying that the earth is round like a pancake, not round like a ball, and (c) says that the earth has an end/edge (Questions 15/16). The other criteria for this concept were that the child says that people can fall down from the edge of the earth (Question 17), and that there is ground, or water below the earth (Question 20). Although a number of children explained the flat/sphere conflict by saying that the earth is like a "thick pancake" rather than "round like a ball," only one child met all criteria for inclusion in this concept. Here is an example from this child's responses to our earth shape questions.

Jamie (3rd grade)
E: What is the shape of the earth?
C: Round.
E: Which way do we look to see the earth?
C: I don't know.
E: Well, think about it.
C: Probably in the sky.
......
E: Can you draw a picture of the earth? (Child draws the picture appearing in Figure 3.)

[Insert Figure 3 about here.]

E: How come here the earth is flat but before you made it round?
C: Just because I thought it was round.
E: So what do you think it is?
C: I think it is round.

E: Then how come it looks flat here?
C: I don't know.
E: Maybe we'll come back to that. If you walked for many days in a straight line where would you end up?
C: Probably in another planet.
E: Could you ever reach the end of the earth?
C: Yes, if you walked long enough.
E: Could you fall off that end?
C: Yes, probably.
......

At the end of the interview, the child was asked some questions over again.

E: Now I want to go back for just a moment and ask a couple of questions . . . What did you say the shape of the earth was?
C: Round.
E: And we said this is a house on earth and it looks . . .
C: Flat.
E: Now, how can that be?
C: Maybe it's just flat.
E: Maybe it's just flat?
C: The earth.
E: Let's just take some of this (clay). Why don't you make the shape of the earth with this?
C: You mean what I think it is?
E: Yes, whatever you think it is . . .
(Child shapes up the clay like a disc)
E: Now, can people live here? (on top)
C: Yes.
E: Can they live under here? (bottom of disc)
C: No.

Rectangular earth concept. The expected pattern of responses for this concept is shown in Table 10. There was only one child who held this concept. This child drew a rectangle to indicate the earth's shape, placed the moon and stars on top of the rectangle and drew a horizontal line to indicate the sky. This child also drew the people and placed Urbana and China inside the rectangle, said that there is an edge to the earth from which people could fall down, and thought that there was ground and dirt below the earth. An example from this child's responses is given below.

Donald (1st Grade)
E: What is the shape of the Earth?
C: I don't know.
E: Which way do we look to see the Earth?
C: Left.
E: What is above the Earth?
C: God . . .
E. Draw a picture of the Earth.
C: I don't know how it looks like. All I know is clouds. It's all blue up there. A rectangle? I mean a long thing like this.

[Insert Figure 4 about here.]

E: This is a picture of a house sitting on the earth and here the earth is flat. Do you think the earth is flat?

C: Mine is too.
E: Show me where the people live.
C: In a house (draws house) on the Earth.
E: If you walked and walked for many days in a straight line, where would we end up?
C: In Illinois.
E: What if we kept walking.
F: Past! I don't know!
E: Would you ever reach the edge of the earth?
C: He would.
E: Is there an edge to the Earth?
C: Yes.
E: Could you fall off the edge of the earth?
C: No. Because. Yes you will.

Dual earth concept. The expected pattern of responses for placement in this concept are shown in Table 10. The responses of all the children who were placed in this category are shown in Table 12.

[Insert Table 12 about here.]

This concept covered two kinds of children: (a) four children who said explicitly in the course of answering one of the questions that there are two earths (a flat one on which we live, and one round one which is up in the sky), and (b) five children who did not explicitly state that there are two earths, but answered our questions as if they believed so. Most of these children insisted that the earth is round like a ball, not like a pancake, but they said that the earth has an end/edge (Questions 15/16), from which people can fall down (Question 17), and that there is "ground," or "us" below the earth (Question 20). These children also indicated either that people live on a flat line outside the circle (Question 13) or drew the circle depicting the earth inside a square frame (Question 11). Finally, all but one child in this category said that you look "up" to see the earth, a response consistent with the dual earth concept.

Here is a characteristic example from this concept.

Darcy (3rd grade)

E: What is the shape of the earth?
C: Round.
E: How do you know the earth is round?
C: Because it looks like a ball.
E: Which way do we look to see the earth?
C: Up.
E: What is above the earth?
C: The sky.
E: What is below the earth?
C: I don't know.
E: What is to the sides of the earth?
C: Clouds.
E: Make a picture of the earth so that its real shape shows. (Child makes drawing shown in Figure 5.)

[Insert Figure 5 about here.]

E: Now show me where the people live.
C: Child draws house at the border of the paper.

E: Can you show me in your picture, where people live. . . . Where in your picture might people live, Darcy?
C: Down over here?
(Child draws another house along the same border.)
E: Here is a picture of a house. This house is on the earth isn't it?
E: How come here the earth is flat but before you made it round?
C: I don't know.
E: Any ideas at all? Why don't you think about it for a minute. Is the earth really round?
C: No.
E: It's not really round. Well, what shape is it?
C: Yaa. It's round.
E: Then how come it looks flat here?
C: Because it's on the ground.
E: But why does that make it look flat?
C: Because the ground's flat.
E: But the shape of the earth is . . .
C: Round.
E: Ok, we might come back to that some other time.
E: If you walked and walked for many days in a straight line where would you end up?
C: I don't know.
E: Well think about it a minute.
C: On earth.
E: Would you ever reach the edge of the earth?
C: No.
E: Why not?
C: Because it's so high.
E: Because what's so high?
C: The earth.
E: The earth is so high?
E: Could you fall off the edge of the earth?
C: Yes.
E: You could fall off the edge? (Experimenter draws a person upside down.) Would this person fall?
C: Yes.
E: Where would he fall?
C: Down on the ground.

Questionable sphere concept. All the children who were placed in this category had some difficulty reconciling their perception of a flat earth with the information that the earth is a sphere, as can be seen in Table 13. These children answered our questions as if they believed that the earth is a sphere but their responses to Question 14, which required an explanation of the flat/sphere conflict, appeared to reveal the presence of an assimilatory concept. For example, these children said that the earth is round but people live on flat pieces of land, that it is like a truncated sphere or like a thick pancake. Most of these children also deviated from the spherical earth concept in that they drew a horizontal line to indicate the sky in Question 12. Some of these children could probably be assigned to a "truncated sphere" or "thick pancake" concept if we had used a less strict set of criteria; for others it was not possible to determine exactly what concept of the earth they had, if any.

[Insert Table 13 about here.]

Mixed concepts. This group included 10 children with mixed patterns of responses for which no consistent concept could be identified. Five of these children insisted that the earth is round but

deviated from the sphere earth concept first in that they all said that there is an edge to the earth and second in that they gave at least one of the following responses: said "circle" to Question 1, said "up" to Question 3, used a horizontal line to indicate the sky, or drew the moon and stars inside the circle. Two children gave all of the above mentioned responses but said there is no edge to the earth. Finally, two children gave responses more consistent with the inside the sphere concept except that they said that there is an edge to the earth from which one can fall off. One of these children deviated from the inside-the-sphere concept in other respects as well. This child said that there is ground or dirt below the earth (Question 20) and mentioned that when people fall off the edge of the earth they fall on the ground below, a response consistent with the dual earth concept. It is possible that this child and some of the other children did not have an internally consistent concept of the earth's shape. For others it is possible that they had a consistent concept which we were not able to identify.

Frequency of earth shape concepts Table 14 shows the frequency of the identified earth shape concepts by grade. As can be seen, there is a developmental progression of the concepts held by these children. Most first grade children held a dual earth concept or mixed concepts. Most of the third and fifth grade children held sphere, questionable sphere or inside-the-earth concepts.

[Insert Table 14 about here.]

Gravity

Children's understanding of gravity was investigated by asking two series of questions. In the first series the children were asked, "Does anyone live here at the bottom of the Earth?" (Question 20a), then they were shown the drawing of a person standing upside down at the bottom of a circle meant to depict the earth (see Table 15), and were asked, "Would this person fall?" (Question 20bb), and then "why" or "why not?"

[Insert Table 15 about here.]

About half of the children at grade 1 and one-quarter of the children at grades 3 and 5 gave responses indicating that they had a naive concept of gravity according to which objects fall down within a single frame of reference. Most of these children said that people cannot live at the bottom of the earth and that the man would fall. The second series of gravity questions originally used by Nussbaum and Novak (1976) were asked with respect to a ball held by the man at the bottom of the Earth (Table 16). The children were asked, "If this person had a ball in his hand and dropped it, where would the ball go?" (Question 20bc) and "Draw the direction of the ball." Only 27 children gave the correct response to this category (4/20 first graders, 12/20 third graders and 11/20 fifth graders). The remaining children gave various incorrect responses.

[Insert Table 16 about here.]

The following are some examples from the responses of children who had a naive concept of gravity.

Betsy's (1st Grade) (Dual earth concept)

E: Would this person fall?
C: Yes.
E: If this person had a ball in his hand and dropped it, where would the ball go?
C: Down here (shows the ball falling off the earth).
E: Why?
C: Cause. The boy ain't hanging on to it tight.
E: Why would it fall there?
C: I don't know.

E: Tell me in this picture what is down here below the earth?
C: Grass.

Amanda (1st Grade) (Dual earth concept)
E: Does anyone live here at the bottom of the earth?
C: No. Because it would probably be dangerous for living there.
E: Why would it be dangerous?
C: Because it would be the edge of the earth and if a little kid was outside and nobody was watching him they could fall.
E: Where would they fall?
C: Into space.
E: Where would they fall?
C: Probably in other planets.

Luther (5th Grade) (Inside-the-sphere concept)
E: Does anyone live here at the bottom of the earth?
C: No.
E: Why?
C: Because it's too hot. They would burn up.
E: Would they fall off?
C: No.
E: Why not?
C: Because you can't come to the edge of it to fall off. But you can get off the earth with rockets, because they go through the atmosphere.
E: Would this person fall (draws person standing upside down at the bottom of the earth)?
C: No.
E: Why not?
C: Because there is no atmosphere. He'd just float around.
E: If this person had a ball in his hand and dropped it where would the ball go?
C: It would just float up.
E: Why?
C: Because there is no atmosphere or gravity.

Fifteen children said that the man standing at the bottom of the earth would not fall (Table 15). The proportion mentioning "gravity" as an explanation for this response increased with age (2 first graders, 5 third graders and 8 fifth graders). Here is an example of that type of response.

Rich (5th Grade) (Sphere concept)
E: Does anyone live here at the bottom of the earth?
C: No.
E: Why not?
C: It's too cold. Some animals do.
E: Would they fall off?
C: No.
E: Why not?
C: Because there's an atmosphere around the earth.
E: Would this person fall (experimenter draws person upside down)?
C: No.
E: Why not?
C: Cause, well, he can't because of gravity.
E: If this person had a ball in his hand and dropped it, where would the ball go?

C: (Shows ball going toward earth) Because the gravity forces it down.
E: Tell me in this picture what is down here below the earth?
C: Space.

We placed the children in six gravity concepts outlined in Table 17. The children who gave correct responses to both gravity questions were placed in the concept "correct gravity." We did not assume that these children had a sophisticated understanding of gravity, but only an understanding of gravity enough to understand that people at the bottom of the earth will not fall off. The concept "Gravity-inside-the-sphere" was meant to capture the children who said that people can live at the bottom of the earth to the verbal question (apparently interpreting "bottom of the earth" to mean the lower part inside the earth) but when they saw the drawing of the man standing upside down outside the earth they said that the man would fall down.

[Insert Table 17 about here.]

The children who said that the man would not fall but that the ball would fall were placed in the category "mixed gravity," while the children who said that both the man and the ball would fall down, away from the earth were placed in the "naive gravity" concept. Table 18 shows the frequency of responses to these concepts as a function of grade. As expected most first graders had a naive concept of gravity and the probability of having a correct gravity concept increased with age.

[Insert Table 18 about here.]

Relationships Between Earth Shape and Gravity Concepts

Table 19 shows the relationship between earth shape and gravity concepts. As expected, the probability of being assigned to the "Gravity" concept was far greater for the children whose earth shape conceptions were closer to the sphere concept (sphere, questionable sphere, inside-the-sphere) as compared to those who were not (dual-earth, rectangular earth, disk).

[Insert Table 19 about here.]

Two children assigned to the sphere earth concept were not assigned to the "gravity" concept category. Apparently, these children believed that the earth is a sphere but thought that people live only on the top of it. On the other hand, there were a number of children who knew that people do not fall off from the bottom of the earth, but had questionable sphere, inside-the-sphere, or mixed earth shape concepts. Apparently, knowledge about gravity is not a sufficient condition for having a sphere earth shape concept.

Discussion

Consistency vs. Fragmentation

The results of this study showed that most of the children used a well defined and consistent earth shape concept to answer our questions but that this concept was not always the sphere concept. Only 18 of the 60 children investigated were found to use a sphere earth concept consistently and two of these children thought that people live only at the top of the sphere. Neither was it the case that the children used a naive concept of a flat earth totally uncontaminated by adult/scientific notions. Only one child in our sample did *not* say that the earth is round or a circle. Most of the children used concepts of the earth which showed a combination of naive and scientific views. We identified three clear assimilatory concepts: the dual earth, the disc earth and the inside-the-sphere concepts. The children who had a dual earth concept believed that there are two earths, a round one which is up in the sky and a flat one on which people live. The children with a disc concept thought that the earth is both flat and round and that it has an edge. Finally, some children believed that the earth is round like

a sphere but that people live inside the sphere. There were two variations of this inside-the-sphere concept: In one, the earth was conceptualized to be a hollow sphere with people living deep inside it. In the other, the earth was thought to consist of two hemispheres; the lower one on which people lived and the top one which consisted of the sky covering the lower hemisphere like a transparent dome.

Ten children (mostly third and fifth graders) were placed in a questionable sphere category. These children were consistent in answering almost all our generative questions as if they believed that the earth is a sphere but their responses to the explanatory question regarding the flat/sphere conflict (Question 14) revealed various misconceptions about the earth's shape. Some of these children said that the earth is like a truncated sphere, others thought that the earth is like a thick pancake, and others simply said that people live on flat pieces of land. It was clear that these children had particular difficulty in reconciling their perceptual experience of a flat earth with the information that the earth is round.

The remaining nine children (seven were first graders) responded to our questions sometimes in ways consistent with a sphere earth concept, and other times in ways consistent with a disc or an inside-the-sphere concept. We do not know at this point whether these children were genuinely inconsistent or had a consistent concept of the earth's shape which we could not identify. In follow-up studies already in progress we ask additional generative questions and have children select physical models and construct models from playdough in an effort to better identify their conceptual knowledge. It should be noted that our results for consistent classifications may be underestimates since with our methodology measurement error will lead to actually consistent children being classified as inconsistent.

The success in identifying consistent concepts for the great majority of the children in our sample shows that children's conceptual knowledge is not as fragmented and unconnected as some theorists have argued (e.g., di Sessa, 1988; Solomon, 1983). It appears that children try to synthesize the information they receive from their everyday experience and from adults in a meaningful and internally consistent way. Children's synthetic attempts are not different in kind from scientists' attempts to construct or modify theories and in this respect children are like scientists.

It could be objected that some of the concepts we identified (particularly the assimilatory ones) may not be precompiled but may spring from mental models constructed by the children on the spot on the basis of relevant information in their global theories. In our view this issue is not crucial for our position. Whether precompiled or not, the use of relatively stable knowledge structures indicates that children are (a) interested and capable of connecting their knowledge fragments and (b) sensitive to the internal consistency of their synthetic attempts. Nevertheless, the finding that we would not identify a consistent earth shape concept for some children in our sample suggests that there may be important individual differences with respect to such theory construction, a topic which will be interesting to pursue in future work.

The Robustness of Naive Concepts

Although the adult culture provides massive exposure to the idea that the earth is a sphere, some children come to believe that the earth is round like a disc, that people live inside the earth or that there are two earths. There is no doubt that such assimilatory concepts of the earth's shape are child generated. The question is, why do children need to construct such concepts of the earth's shape?

One of the reasons why children may construct assimilatory concepts is because they find it very difficult to give up the idea that the earth is not flat. Assimilatory concepts succeed in reconciling the phenomenal experience of a flat earth with the adult information that the earth is a sphere. All the assimilatory concepts we have identified are based on the belief that the earth is both flat and round at the same time. The children with the dual earth concept believe that there are two earths, one round, and one flat. The children with a disc concept interpret round to mean round but flat; and the children

with the inside-the-sphere concept believe that the earth is a sphere but that people live on flat ground inside the earth. There would be no reason for children to form these systematic and robust misconceptions if they did not believe that the earth is flat in the first place.

Assimilatory concepts show that children are not "blank slates" with respect to the earth's shape when they receive the information that the earth is a sphere but that they have constructed an initial, naive concept of the earth according to which the earth is flat. This naive concept is difficult to give up otherwise the children in our sample would have readily replaced it with the sphere concept instead of forming an assimilatory one. More direct confirmation of the hypothesis that children start by forming an initial naive concept of a flat earth has been obtained in our studies of preschool children (Vosniadou & Brewer, in preparation) and in our cross-cultural work (Brewer, Herdrich, & Vosniadou, submitted; Samarapungavan & Vosniadou, in preparation; Vosniadou & Brewer, in press).

Naive and Assimilatory Concepts are Embedded Within Global Theories

Children's concepts of the earth are not composed only of the belief that the earth is flat. An examination of the specific assimilatory concepts we have uncovered shows that they represent attempts on the part of the children to synthesize not one but a number of discrete beliefs about the earth.

Some of these beliefs are the belief that the ground does not extend indefinitely but has an edge, and that people can fall off from that edge, that there is ground or water all the way down below the earth, that people live on the flat top of the earth, that the sky is only on top of the earth, and that things fall down when you drop them.

The belief that the earth has an end/edge is found in the naive concept and is retained in the disc and the inside-the-earth concepts but not the sphere and the questionable sphere concepts. The children who have sphere or questionable sphere concepts have understood that the earth does not have an end/edge and that if one were to walk for many days one would come back to where one started.

The belief that people can fall off the earth's edge differentiates the inside the earth concept from the naive and disc concept. The children with the inside-the-sphere concept believe that there is an edge to the earth but think that we cannot fall down from it either because the edge is too high up and people cannot reach it, or because the earth is enclosed by the sky. Another belief that differentiates the sphere, questionable sphere and inside-the-sphere children from the other children is the belief that the earth is suspended in space. The children who hold a naive concept appear to believe that there is ground or water all the way down below the earth. Finally, there is the belief that things fall down when you drop them which differentiates the children who have a sphere earth concept with gravity from the ones who do not know about gravity and think that people live only at the top of the earth.

We think that these ontological beliefs are constructed by the children on the basis of their everyday experience under the constraints of their global theories. Naive and assimilatory concepts are generated out of these ontological beliefs. In addition to a theory of ontology children seem to also have an epistemological theory which further constrains their concepts. Part of this epistemological theory is the belief that (a) that ontological beliefs represent the true state of affairs about the world and (b) adults are usually right.

If children did not believe that their ontological beliefs represent the way the world really is there would be no reason to form assimilatory concepts of the earth. They would simply change their beliefs and adopt the adult model that the earth is a sphere. The formation of assimilatory concepts indicates that children are operating under the epistemological constraint that their ontological beliefs are fundamentally correct. Assimilatory concepts also presuppose the belief that adults are right. If children did not believe that adults are right they would have no difficulty rejecting the adult

information and retaining their original naive views. When children construct an assimilatory concept they try to retain their ontological beliefs in a way that does not contradict adult teachings.

In summary, we think that the genesis of an assimilatory concept can be conceptualized in the following way. When children read in a book or hear from an adult that the earth is a sphere they do not want to believe that the adult information is wrong but find it hard to reconcile it with their ontological beliefs. Because children believe that their ontological beliefs represent the true state of affairs about the world they are not likely to question them. Rather, they believe that they have misunderstood what the adults really mean when they say that the earth is round. In trying to interpret the adult information in a way that does not contradict their ontological beliefs children construct assimilatory concepts or develop unassimilated internally inconsistent concepts.

Theory Articulation vs. Theory Restructuring

Conceptual change has often been conceptualized in terms of the differentiation and hierarchical integration of children's initial conceptual structures. This proposal put forward originally by Werner (1948) has found many proponents in recent years (Carey, 1985; Chi, in press; Keil, 1979, 1983; Smith, Carey, & Wiser, 1985), although there are important differences in the way differentiation and hierarchical integration are conceptualized by different researchers. For example, Keil (1979, 1983) sees differentiation as the articulation of existing structures whereas according to Carey and her colleagues (Carey, 1985; Smith, Carey, & Wiser, 1985), differentiation involves theory change.

For some concepts, in some domains, restructuring may be achieved through the differentiation or coalescence of existing conceptual structures. However, the change from a concept that the earth is flat to a concept that the earth is a sphere cannot be accounted for in terms of differentiation or coalescence. Neither can it be accounted for by a model such as the one proposed by Chi (in press) in which two separate and previously unconnected microstructures become hierarchically organized. Assuming that the information that the earth is a sphere is originally stored as a separate microstructure Chi's model can explain how the dual earth assimilatory concept is formed, but it cannot explain how children generate the disc or the inside-the-sphere assimilatory concepts.

It could be argued that the change from a flat earth concept to a round earth concept does not require the articulation or the restructuring of an existing theoretical structure but that it simply involves the replacement of the property "flat" with the property "round." This position does not explain why children find it so difficult to make the change from the flat to the round earth concept neither does it explain the formation of assimilatory concepts.

It is important to note that when children change to a sphere earth shape concept they have not lost the information that in the observed, everyday, world the ground is flat. What they have done is to change their interpretation of this observation from one according to which the earth is flat one according to which to the earth is a sphere. This change in explanatory framework is an important characteristic of theory restructuring.

Restructuring via Assimilation

Although our data is cross-sectional and not longitudinal the progression of earth shape concepts we have obtained from the younger to the older children provides us with interesting information regarding the processes involved in theory restructuring. First, the finding that the younger children in our sample were more likely to form dual earth concepts or hold internally inconsistent concepts suggests that as children are first exposed to the information that the earth is round they are likely to accept it as a fact and store it as separate structure, in a way similar to that described by Chi (in press).

Second, the presence of the disc and inside-the-earth concepts shows that when children realize the contradiction between the two pieces of information they try to resolve it by assimilating the

information that the earth is a sphere to their existing structures. As described earlier this process of assimilation results from changing some but not all of the ontological beliefs that give rise to a naive concept of the earth while at the same time trying to synthesize them into a coherent and internally consistent whole.

Accommodation, or restructuring, is the last step in this long, slow process of knowledge acquisition. It is achieved when most of the ontological beliefs that give rise to the naive concept have been replaced by a different explanatory framework. The explanatory framework that modifies the relevant ontological beliefs provides the basis for forming a domain-specific theory of astronomy.

The finding that the restructuring of a naive concept is a slow and gradual one does not agree with the position that theory change involves Gestalt-like switches which has been put forward by Kuhn (1962). The position that theory change involves a sudden and dramatic insight has been criticized by philosophers of science (Laudan, 1984; Toulmin, 1972). In recent years Kuhn has modified his position considerably (Kuhn, 1982) but has not altogether rejected the notion that restructuring involves a sudden insight, particularly in the case of the historian of science who is trying to understand an earlier theory radically different in its explanatory framework from the one they currently hold.

It could be argued that in the domain of astronomy children are in some respects in a position analogous to that of a historian of science, in that they need to understand a conceptual system which is radically different from their naive conceptions of the cosmos. To the extent that we could generalize from our study of the concept of the earth's shape, our results suggest that theory change is a slow and gradual process and not one that is achieved in a sudden Gestalt-switch fashion.

It is not clear at this point why children find it so difficult to change their naive concepts. There are a number of possibilities which need to be examined in follow-up studies. As was mentioned earlier, children do not seem to question the truth of their ontological beliefs spontaneously. In that respect, ontological beliefs are not like the hypotheses or assumptions of a particular scientific theory but more like the unquestionable assumptions and presuppositions defining the research paradigm within which a scientist operates. In order to restructure their naive conceptions, children need to be provided with enough reasons to question their ontological beliefs and with a different explanatory framework to replace the one they have constructed on the basis of their everyday experience. Unfortunately, the kind of instruction children receive during the elementary school years does not do that (Vosniadou, 1988, in preparation).

Differences With Piaget's Theory

We have argued that a theory of conceptual change involves not only the articulation of existing theoretical structures but also their restructuring. The kind of restructuring we have described can be conceptualized as requiring the emergence of a domain-specific theory of astronomy out of a global theory or the replacement of one domain-specific theory with another (if children's naive and assimilatory concepts are assumed to emerge out of domain-specific conceptual structures). The theoretical framework which we have described also allows the possibility for global restructurings to occur when most of the assumptions associated with a global theory are replaced with a different explanatory framework.

Our differences with Piaget's theory is not on the issue of global vs. domain-specific restructuring but rather on the issue of how restructuring is achieved. We think that both domain-specific and global restructurings can be accounted for in terms of differences in explanatory framework, analogous to theory changes in the history of science, rather than in qualitative differences in children's capacity to think in terms of extensional logic.

Methodological Issues

Last, but not least, this paper makes a contribution towards a methodology which can lead from children's individual responses to the concepts that underlie them and which can be used not only in the domain of astronomy but in most other domains.

A crucial aspect of this methodology is the construct of the mental model. The notion of the mental model has been used extensively in recent work in cognitive science (Gentner & Stevens, 1983; Johnson-Laird, 1983), but without making clear how mental models are related to concepts and whether they are meant to represent a structural or a procedural component of the human cognitive system. In our theoretical framework we treat mental models as products of the procedural component, in other words as mental representations which are generated on the spot out of the existing conceptual structures in order to deal with a particular problem or in order to answer a question. As such, mental models can provide important information about the conceptual structures from which they are generated.

Of methodological interest is also the procedure we developed for looking at the agreement between the obtained responses to the individual questions and those derived a priori on the basis of the hypothesized mental modes. This procedure can provide information about the degree to which children have formed internally consistent concepts.

Finally, the construct of the generative question is an important one. Generative questions are the kinds of questions that differentiate between two competing mental models. In this study generative questions enabled us to differentiate responses consistent with a naive concept from those consistent with a sphere concept. We believe that similar generative questions can be constructed in other domains to differentiate among different possible conceptions of the same phenomena.

Conclusions

We have argued that children form a naive concept of the earth according to which the earth is flat. The process of restructuring the naive concept of a flat earth to the currently accepted concept of a spherical earth is a slow and gradual one, and one that typically gives rise to intermediate assimilatory concepts. Assimilatory concepts are formed because children try to reconcile certain fundamental ontological beliefs with the information coming from adults that the earth is a sphere. The presence of these assimilatory concepts confirms the hypothesis that children's concept of the earth is embedded within children's ontological and epistemological theories, and that changing this concept requires a kind of theory restructuring which is analogous to radical theory change in the history of science.

References

Abelson, R. P. (1981). Psychological status of the script concept. *American Psychologist, 36*, 715-729.

Anderson, C. W., & Smith, C. L. (1986). *Children's conceptions of light and color: Understanding the role of unseen rays* (Res. Series No. 166). Michigan State University, College of Education, Institute for Research on Teaching.

Berry, A. (1961). *A short history of astronomy: From the earliest times through the nineteenth century.* New York: Dover.

Brewer, W. F., Herdrich, D. J., & Vosniadou, S. (submitted). *A cross-cultural study of children's development of cosmological models: Samoan and American data.*

Brewer, W. F. (1987). Schemas versus mental models in human memory. In P. Morris (Ed.), *Modelling cognition* (pp. 187-197). Chichester: Wiley.

Brewer, W. F., & Nakamura, G. V. (1984). The nature and functions of schemas. In R. S. Wyer, Jr., & T. K. Srull (Eds.), *Handbook of social cognition* (Vol. 1, pp. 119-160). Hillsdale, NJ: Erlbaum.

Brewer, W. F., & Samarapungavan, A. (in press). The child as scientist: Child theories versus scientific theories. In R. R. Hoffman & D. S. Palermo (Eds.), *Cognitive psychology: The state of the art.* Hillsdale, NJ: Erlbaum.

Bruner, J. S., Goodnow, J. J., & Austin, G. A. (1956). *A study of thinking.* New York: Wiley.

Carey, S. (1985). *Conceptual change in childhood.* Cambridge, MA: MIT Press.

Carey, S. (1986). Constraints on semantic development. In W. Demopoulos & A. Marras (Eds.), *Language learning and concept acquisition* (pp. 154-172). Norwood, NJ: Ablex.

Chi, M. T. H. (in press). Children's lack of access and knowledge reorganization: An example from the concept of animism. In F. Weinert & M. Perlmutter (Eds.), *Memory development: Universal changes and individual differences* (pp. 169-194). Hillsdale, NJ: Erlbaum.

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5*, 121-152.

Clement, J. (1982). Students' preconceptions in introductory mechanics. *American Journal of Physics, 50*, 66-71.

Collins, A., & Stevens, A. L. (1984). *Mental models of complex systems* (Report No. 5788). Cambridge, MA: Bolt, Beranek & Newman, Inc.

diSessa, A. A. (1988). Knowledge in pieces. In G. Forman & P. B. Pufall (Eds.), *Constructivism in the computer age* (pp. 49-70). Hillsdale, NJ: Erlbaum.

Driver, R., & Easley, J. (1978). Pupils and paradigms: A review of literature related to concept development in adolescent science students. *Studies in Science Education, 5*, 61-84.

Fodor, J. (1972). Some reflections on L. S. Vygotsky's Thought and Language. *Cognition, 1*, 83-95.

Fodor, J. (1980). Fixation of belief and concept acquisition. In M. Piattelli-Palmarini (Ed.), *Language and learning: The debate between Jean Piaget and Noam Chomsky* (pp. 143-149). Cambridge, MA: Harvard University Press.

Gelman, R., & Gallistel, C. R. (1978). *The child's understanding of number* Cambridge, MA: Harvard University Press.

Gelman, S. A., & Markman, E. M. (1986). Categories and induction in young children. *Cognition, 23*, 183-209.

Gentner, D., & Stevens, A. L. (Eds.) (1983). *Mental models*. Hillsdale, NJ: Erlbaum.

Gombrich, R. F. (1975). Ancient Indian cosmology. In C. Blacker & M. Loewer (Eds.), *Ancient cosmologies* (pp. 110-142). London: Allen & Unwin.

Hanson, N. R. (1958). *Patterns of discovery*. London: Cambridge University Press.

Hawking, S. W. (1988). *A brief history of time: From the big bang to black holes*. New York: Bantam.

Johnson-Laird, P. N. (1983). *Mental models*. Cambridge, MA: Harvard University Press.

Keil, F. C. (1979). *Semantic and conceptual development: An ontological perspective*. Cambridge, MA: Harvard University Press.

Keil, F. C. (1983). On the emergence of semantic and conceptual distinctions. *Journal of Experimental Psychology: General, 112*, 357-385.

Keil, F. C. (1986). The acquisition of natural kinds and artifact terms. In W. Demopoulos & A. Marras (Eds.), *Language learning and concept acquisition* (pp. 133-153). Norwood, NJ: Ablex.

Keil, F. C., & Kelly, M. H. (1986). Theories and constraints on theories. In W. Demopoulos & A. Marras (Eds.), *Language learning and concept acquisition* (pp. 13-183). Norwood, NJ: Ablex.

Kuhn, T. S. (1957). *The Copernican revolution*. Cambridge, MA: Harvard University Press.

Kuhn, T. S. (1962). *The structure of scientific revolutions*. Chicago: University of Chicago Press.

Kuhn, T. S. (1963). The function of dogma in scientific research. In A. C. Crombie (Ed.), *Scientific change* (pp. 347-369). New York: Basic Books.

Kuhn, T. S. (1970). *The structure of scientific revolutions* (2nd ed.). Chicago: University of Chicago Press.

Kuhn, T. S. (1977). *The essential tension*. Chicago: University of Chicago Press.

Kuhn, T. S. (1982). Commensurability, comparability, communicability. In *Proceedings of the biennial meeting of the Philosophy of Science Association* (Vol. 2, pp. 669-688). East Lansing, MI: Philosophy of Science Association.

Lakatos, I. (1970). Falsification and the methodology of scientific research programmes. In I. Lakatos & A. Musgrave (Eds), *Criticism and the growth of knowledge* (pp. 91-195). Cambridge: Cambridge University Press.

Lambert, W. G. (1975). The cosmology of Sumer and Babylon. In C. Blacker & M. Loewe (Eds.), *Ancient cosmologies* (pp. 42-65). London: Allen & Unwin.

Larkin, J. H. (1981). Enriching formal knowledge: A model for learning to solve textbook physics problems. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 311-334). Hillsdale, NJ: Erlbaum.

Laudan, L. (1977). *Progress and its problems*. Berkeley: University of California Press.

Laudan, L. (1984). *Science and values*. Berkeley: University of California Press.

Mali, G. B., & Howe, A. (1979). Development of earth and gravity concepts among Nepali children. *Science Education, 63*, 685-691.

Mandler, J. M. (1983). Representation. In J. H. Flavell & E. M. Markman (Eds.), Cognitive Development: (Vol. 3). *Handbook of Child Psychology* (4th ed., pp. 420-494). New York: Wiley.

McCloskey, M. (1983). Naive theories of motion. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 299-324). Hillsdale, NJ: Erlbaum.

McCloskey, M., & Kargon, R. (1988). The meaning and use of historical models in the study of intuitive physics. In S. Strauss (Ed.). *Ontogeny, philogeny, and historical development* (pp. 49-67). Norwood, NJ: Ablex.

Medin, D. L., Wattenmaker, W. D., & Hampson, S. H. (1987). Family resemblance, conceptual cohesiveness, and category construction. *Cognitive Psychology, 19*, 242-279.

Miller, G. A., & Johnson-Laird, P. N. (1976). *Language and perception*. Cambridge, MA: Harvard University Press.

Murphy, G. L., & Medin, D. L. (1985). The role of theories in conceptual coherence. *Psychological Review, 92*, 289-316.

Neisser, U. (Ed.) (1987). *Concepts and conceptual development: Ecological and intellectual factors in categorization*. Cambridge: Cambridge University Press.

Nelson, K. (1978). How children represent knowledge of their world in and out of language: A preliminary report. In R. S. Siegler (Ed.), *Children's thinking: What develops*? (pp. 255-273). Hillsdale, NJ: Erlbaum.

Nussbaum, J. (1979). Children's conceptions of the earth as a cosmic body: A cross-age study. *Science Education, 63*, 83-93.

Nussbaum, J., & Novak, J. D. (1976). An assessment of children's concepts of the earth utilizing structured interviews. *Science Education, 60*, 535-550.

Osborne, R. J., & Wittrock, M. C. (1983). Learning science: A generative process. *Science Education, 67*, 489-508.

Piaget, J. (1929). *The child's conception of the world*. London: Routledge & Kegan Paul.

Piaget, J. (1962). *Play, dreams and imitation in childhood*. New York: Norton.

Plumley, J. M. (1975). The cosmology of ancient Egypt. In C. Blacker & M. Loewer (Eds.), *Ancient cosmologies* (pp. 17-41). London: Allen & Unwin.

Rosch, E., & Mervis, C. B. (1975). Family resemblances: Studies in the internal structure of categories. *Cognitive Psychology, 7*, 573-605.

Rosch, E., Mervis, C. B., Gray, W. D., Johnson, D. M., & Boyes-Braem, P. (1976). Basic objects in natural categories. *Cognitive Psychology, 8*, 382-439.

Ross, G. S. (1980). Categorization in 1- to 2-year-olds. *Developmental Psychology, 16*, 391-396.

Rozin, P. (1976). The evolution of intelligence and access to the cognitive unconscious. In J. M. Sprague & A. A. Epstein (Eds.), *Progress in psychobiology and physiological psychology* (pp. 245-276). New York: Academic Press.

Rumelhart, D. E. (1980). Schemata: The building blocks of cognition. In R. J. Spiro, B. C. Bruce, & W. F. Brewer (Eds.), *Theoretical issues in reading comprehension* (pp. 33-58). Hillsdale, NJ: Erlbaum.

Samarapungavan, A., & Vosniadou, S. (in preparation). *What children from India think about the earth, sun, moon and stars*. Urbana: University of Illinois, Center for the Study of Reading.

Smith, C., Carey, S., & Wiser, M. (1985). On differentiation: A case study of the development of the concepts of size, weight, and density. *Cognition, 21*, 177-237.

Smith, E. E., & Medin, D. L. (1981). *Categories and concepts*. Cambridge, MA: Harvard University Press.

Sneider, C., & Pulos, S. (1983). Children's cosmographics: Understanding the earth's shape and gravity. *Science Education, 67*, 205-221.

Solomon, J. (1983). Thinking in two worlds of knowledge. In H. Helm & J. D. Novak (Eds.), *Proceedings of the international seminar: Misconceptions in science and mathematics* (pp. 127-132). Ithaca, NY: Cornell University.

Sugarman, S. L. (1983). *Children's early thought*. Cambridge: Cambridge University Press.

Toulmin, S. (1961). *Foresight and understanding*. New York: Harper & Row.

Toulmin, S. (1972). *Human understanding*. Princeton, NJ: Princeton University Press.

Toulmin, S., & Goodfield, J. (1961). *The fabric of the heavens: The development of astronomy and dynamics*. New York: Harper & Row.

Vosniadou, S. (1988, April). Knowledge restructuring and science instruction. In J. Greeno (Chair), *Conceptual models of science learning and science instruction*. Symposium conducted at the annual meeting of the American Educational Research Association, New Orleans.

Vosniadou, S. (in press). Analogical reasoning as a mechanism in knowledge acquisition: A developmental perspective. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning*. Cambridge: Cambridge University Press.

Vosniadou, S. (in preparation). *Theories of conceptual change in development*.

Vosniadou, S., & Brewer, W. F. (1987). Theories of knowledge restructuring in development. *Review of Educational Research, 57*, 51-67.

Vosniadou, S., & Brewer, W. F. (in press). A cross-cultural investigation of children's acquisition of knowledge in observational astronomy: Greek and American data. In H. Mandl, E. DeCorte, N. Bennett, & H. F. Friedrich (Eds.), *Learning and instruction: European research in an international context* Oxford: Pergamon.

Vosniadou, S., & Brewer, W. F. (in preparation). *Looking at the sky: What children think about the sun, moon and stars*. Urbana: University of Illinois, Center for the Study of Reading.

Vosniadou, S., & Ortony, A. (1983). The emergence of the literal- metaphorical-anomalous distinction in young children. *Child Development, 54*, 154-161.

Vosniadou, S., & Ortony, A. (in press). *Similarity and analogical reasoning*. Cambridge: Cambridge University Press.

Vygotsky, L. (1934/1986). *Thought and language*. Cambridge, MA: MIT Press.

Werner, H. (1948). *Comparative psychology of mental development*. New York: International Universities Press.

Wiser, M., & Carey, S. (1983). When heat and temperature were one. In D Gentner & L. A. Stevens (Eds.), *Mental models* (pp. 267-297). Hillsdale, NJ: Erlbaum.

Author Notes

We would like to thank the principal, the teachers and the children of Washington School in Urbana, Illinois for their help in carrying out the research reported in this paper. We also wish to thank Marlo Schommer, Marcy Dorfman, and Ann Jolly for their help in testing the children and scoring of the data and Marcy Dorfman, Jack Easley, David Herdrich, Doug Medin, and Ala Samarapungavan for comments on an earlier draft.

Correspondence should be addressed to Dr. Stella Vosniadou, Center for the Study of Reading, University of Illinois at Urbana-Champaign, 51 Gerty Drive, Champaign, IL 61820.

Figure Captions

Figure 1. Drawing of the Earth, Sun, Moon and Stars by Ethan, Grade 1 (Sphere Concept)

Figure 2. Drawing of the Earth, Sun, Moon, and Stars by Veronica, Grade 3 (Inside-the-Sphere Concept)

Figure 3. Drawing of the Earth, Sun, Moon, and Stars by Jamie, Grade 3 (Disc Concept)

Figure 4. Drawing of the Earth, Sun, Moon, and Stars by Donald, Grade 1 (Rectangular Earth Concept)

Figure 5. Drawing of the Earth, Sun, Moon, and Stars by Darcy, Grade 3 (dual Earth Concept)

Table 1

Frequency of Responses to Question 1, "What is the shape of the earth?"

	Response	Grade 1	3	5	Total
1.	Don't know	1	0	0	1
2.	Round	2	17	18	37
3.	Circle	14	2	0	16
4.	Round like a ball or sphere	3	1	1	5
5.	Oval	0	0	1	1
Total		20	20	20	60

Table 2

Frequency of Responses to Question 3, "Which way do we look to see the earth?"

Response	Grade 1	3	5	Total
1. Down	2	6	7	15
2. Up	12	6	5	23
3. Sideways	3	2	2	7
4. Everywhere, all around	2	5	5	12
5. To the back or to the front	1	1	1	3
Total	20	20	20	60

Table 3

Frequency of Responses to Question 11, "Can you draw a picture of the earth?"

	Grade			
R .sponse	1	3	5	Total
1. Circle	15	20	19	54
2. Rectangle	1	0	0	1
3. Circle within swuare frame	1	0	0	1
4. Oval	1	0	1	2
5. Straight line changed to circle	2	0	0	2
Total	20	20	20	60

Table 4

Frequency of Responses to Question 12, "Now on this drawing, show me where the moon and stars go." "Now draw the sky."

Response	Grade 1	3	5	Total
1. Moon and stars above circle horizontal line for sky.	3	4	2	9
2. Moon and stars above circle, no horizontal line.	2	6	5	13
3. Moon and stars all around circle, horizontal line.	3	3	0	6
4. Moon and stars all around circle, no horizontal line.	3	6	9	28
5. Moon and stars inside circle, no horizontal line.	3	1	4	8
6. Moon and stars above circle, horizontal line at bottom of circle.	2	0	0	2
7. Moon and stars all around circle and horizontal line at bottom of circle.	2	0	0	2
8. Other	2	0	0	2
Total	20	20	20	60

Table 5

Frequency of Responses to Question 13, "Show me where the people live."

Response	Grade 1	3	5	Total
1. Inside the circle	15	17	18	50
2. Standing on the perimeter of the circle	2	0	0	2
3. On straight line outside the circle	1	0	0	1
4. As above, but changed after questioning to inside the circle	1	1	0	2
5. On flat line inside the circle	0	1	2	3
6. Inside rectangle	1	0	0	1
7. Missing	0	1	0	1
Total	20	20	20	60

Table 6

Frequency of Responses to Question 14, "How come here the earth is flat but before you made it round?"

Response	1	3	5	Total
	Grade			
1. Not applicable. (Child thinks the earth is flat.)	1	0	0	1
2. Dc n't know/no response	1	0	0	1
3. Changed from round earth to rectangle earth	1	0	0	1
4. Child appears not to recognize the conflict	2	0	0	2
5. The earth is round like a disc	1	3	0	4
6. The earth looks round but inside i. is flat	3	5	6	14
7. The earth is round but we live on flat piece(s) on the top	0	1	0	1
8. There are two earths	2	2	0	4
9. The earth is round but we live on flat pieces of land	1	0	2	3
10. Child insists that the earth is round, recognizes conflict, cannot explain it	5	6	9	20
11. Child gives an adequate explanation	2	3	2	7
12. Other	1	0	1	2
Total	20	20	20	60

Table 7

Frequency of Responses to Questions 15 & 16, "If you walked and walked for many days in a straight line, where would you end up? Would you ever reach the edge of the earth?" and "Is there an edge to the earth?"

Response	Grade 1	Grade 3	Grade 5	Total
1. Yes, there is an end/edge	12	4	0	16
2. Yes, there is an end/edge but we cannot reach it because we are inside the earth	2	2	2	6
3. No end/edge and no explanation	4	4	7	15
4. No end/edge; you come back to where you started	2	5	8	15
5. No end/edge because the earth is round	0	4	3	7
6. No end/edge but the earth is up on the sky	0	1	0	1
Total	20	20	20	60

Table 8

Frequency of Responses to Question 176, "Could you fall off the edge of the earth?"

Response	Grade 1	3	5	Total
1. Don't know, or no response	2	0	0	2
2. Not applicable (there is no end/edge)	5	10	17	32
3. Yes, you can fall off	9	3	0	12
4. Yes, you will fall on the ground (the ground being underneath the earth)	1	1	0	2
5. No (and no explanation)	1	1	1	3
6. No, you are inside the sphere	1	2	1	4
7. No, gravity will hold you	1	0	1	2
8. Other	0	3	0	3
Total	20	20	20	60

Table 9

Frequency of responses to Question 20, "Tell me in this picture what is down here below the earth?"

Response	Grade 1	3	5	Total
1. Don't know	4	0	0	4
2. Sky, atmosphere, clouds	4	6	3	13
3. Solar Objects	5	7	6	18
4. Space, nothing	1	5	8	14
5. Dirt, ground, grass, land, "us"	6	1	2	9
6. Water	0	1	1	2
Total	20	20	20	60

Table 10. Concepts of the Earth Shape

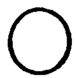
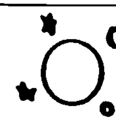
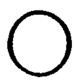
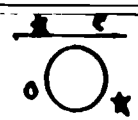
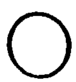
Earth Shape Concepts	What is the shape of the Earth? (Q1)	Which way do we look to see the Earth? (Q3)	Draw a picture of the Earth. (Q11)	Now draw the moon, the stars and the sky. (Q12)	Show me where the people live on the earth. (Q13)	Expl. of flat/sphere conflict (Q14)	Is there an end/edge to the earth? (Q15/16)	Can you fall off that end? (Q17/18)	Where is C-U and where is China? (Q19)	What is down here below the Earth? (Q20)
Sphere	Sphere or Round	Down, all around, sideways		 Moon & stars all around or above. No horizontal line.	 Inside circle or on the periphery of the circle	More or less adequate explanation	No end/edge (You come back to where you started)	Not applicable, can't fall off	Both are inside circle or one is on the other side of the circle	Space, sky, or solar objects
Questionable Sphere	Sphere or Round	Down, all around, sideways		 Moon & stars all around or above. Horizontal line.	 Inside circle or on the periphery of the circle	"Thick pancake" or live on flat pieces of land	No end/edge	Not applicable, can't fall off	Inside circle	Space, sky, or solar objects
Inside the Sphere	Sphere or round	Anything		 Moon & stars inside, above, or all around.	 Inside circle or on flat line inside circle	Earth is flat inside. We live <u>inside</u> the earth	Yes, end/edge but can't reach it because you're inside sphere, or No end/edge	Not applicable, can't fall off	Inside circle	Space, sky, or solar objects

Table 10 (Continued)

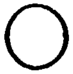
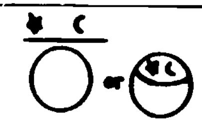
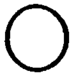
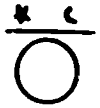
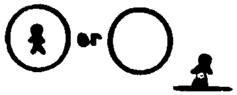
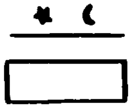
Earth Shape Concepts	What is the shape of the Earth? (Q1)	Which way do we look to see the Earth? (Q3)	Draw a picture of the Earth. (Q11)	Now draw the moon, the stars and the sky. (Q12)	Show me where the people live on the earth. (Q13)	Expl. of flat/sphere conflict (Q14)	Is there an end/edge to the earth? (Q15/16)	Can you fall off that end? (Q17/18)	Where is C-U and where is China? (Q19)	What is down here below the Earth? (Q20)
Disc	Round or circle	Down, all around, sideways		 Moon & stars above or inside. Horizontal line.	 Inside circle	Round like a pancake	Yes end/edge	Yes, you can fall off	Inside circle	Anything
Dual Earth	Round or circle	Up		 Moon & stars on top or bottom. Horizontal line	 Inside circle or on flat line outside circle	There are 2 earths/we live on flat pieces of land	Yes end/edge	Yes, you can fall off	Inside circle or on flat line outside circle	Ground, dirt, "us"
Rectangle	Rectangle	Down, all around, sideways		 Moon & stars above flat earth. Horizontal line.	 Inside rectangle	Not applicable	Yes end/edge	Yes, you can fall off	Inside rectangle	Dirt, ground
Mixed										

Table 11 - Inside the Sphere Concept

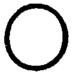
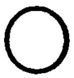
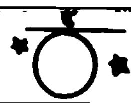
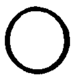
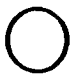
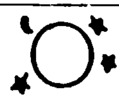
Subjects	What is the shape of the Earth? (Q1)	Which way do we look to see the Earth? (Q3)	Draw a picture of the Earth (Q11)	Now draw the moon, the stars and the sky. (Q12)	Show me where the people live on the earth (Q13)	Expl. of flat/sphere connect (Q14)	Is there an end/edge to the earth? (Q15/16)	Can you fall off that end? (Q17/18)	Where is C.U and where is China? (Q19)	What is down here below the Earth? (Q20)
2	Round	Up				Earth looks round but it is flat inside People live inside the Earth.	There is an end/ edge but we are inside the sphere and the edge is on top of us	No, gravity will hold you	Both inside circle	Solar objects
9	Round	All around				·	No end/edge	N/A	·	Dirt, ground
13	Round	All around				·	Yes, but inside	Can't fall. You are inside.	One is on the other side of circle	Solar objects
33	Round	All around				·	·	·	Both inside circle	Solar objects
30	Round	Up				·	·	·	·	Sky
35	Circle	Down				·	No end/edge	N/A	·	Space
32	Circle	Down				·	No end/edge You come back to where you started	N/A	·	Sky
56	Sphere	All around				·	Yes, but inside	Missing	·	Solar objects

Table 11 (Continued)

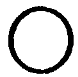
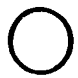
Subjects	What is the shape of the Earth? (Q1)	Which way do we look to see the Earth? (Q3)	Draw a picture of the Earth (Q11)	Now draw the moon, the stars and the sky. (Q12)	Show me where the people live on the earth. (Q13)	Expl of flat/sphere conflict (Q14)	Is there an end/edge to the earth? (Q15/16)	Can you fall off that end? (Q17/18)	Where is C-U and where is China? (Q19)	What is down here below the Earth? (Q20)
48	Circle	Up				*	Yes, but inside	Can't fall. You are inside	*	Solar objects
10	Round	All around				*	No end/edge because the Earth is round	N/A	*	Dirt, ground

Table 12 - Dual Earth Models

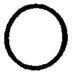
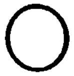
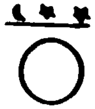
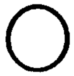
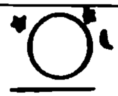
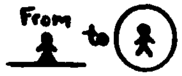
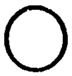
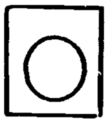
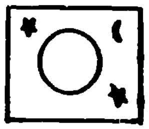
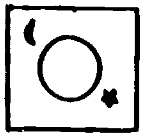
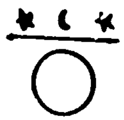
Subjects	What is the shape of the Earth? (Q1)	Which way do we look to see the Earth? (Q3)	Draw a picture of the Earth (Q11)	Now draw the moon, the stars and the sky. (Q12)	Show me where the people live on the earth. (Q13)	Expl. of flat/sphere conflict (Q14)	Is there an end/edge to the earth? (Q15/16)	Can you fall off that end? (Q17/18)	Where is C-U and where is China? (Q19)	What is down here below the Earth? (Q20)
40	Round	Up				Dual earth	No end/edge but Earth is up in the sky	Yes you can fall on the ground	Inside earth drawing	Sky
42	Circle	Up				Dual earth	No end/edge	Not applicable	Inside earth drawing	Sky
59	Circle	Up				Other	Yes end/edge	Yes	Inside earth	Sky
53	Circle	Up	Flat but changes to circle	Other		Change from round to flat	Yes	Yes	Inside earth drawing	Dirt, ground
51	Circle	Up				Don't know	Yes	Yes	Inside earth	Dirt, ground
47	Circle	Up				Round like a pancake	Yes	Yes	On both sides of earth drawing	Don't know
54	Circle	Sideways				Round but we live on flat pieces of land	Yes	Yes	Champaign-Urbana is inside the Earth	Dirt, ground
31	Round	Up				Dual Earth	Yes	Yes	Inside earth drawing	Earth (Earth is flat line under the circle)
	Circle	Up				Dual Earth	Yes	Don't know	Inside earth	Sky

Table 13 - Questionable Sphere Models

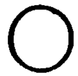
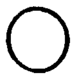
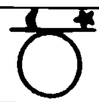
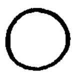
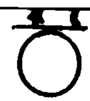
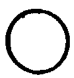
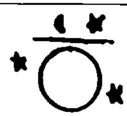
Subjects	What is the shape of the Earth? (Q1)	Which way do we look to see the Earth? (Q3)	Draw a picture of the Earth. (Q11)	Now draw the moon, the stars and the sky (Q12)	Show me where the people live on the earth. (Q13)	Expl. of flat/sphere conflict (Q14)	Is there an end/edge to the earth? (Q15/16)	Can you fall off that end? (Q17/18)	Where is C-U and where is China? (Q19)	What is down here below the Earth? (Q20)
20	Round	All around				Looks flat inside	No end/edge	Not applicable	Both inside circle	Space
8	Sphere	Down				Looks flat inside	No end/edge You come back to where you started	Not applicable	Both inside circle	Neverland
18	Oval	All around				We live on flat pieces of land	-	Not applicable	-	Space
11	Round	Sideways				-	No end/edge	-	-	Solar objects
12	Round	Up				Thick pancake	No end/edge	No	-	Earth (Flat line under circle)
17	Round	Up				Other	-	Not applicable	-	Space
43	Round	All around				Round like a thick pancake	-	-	-	Solar objects
22	Round	Up				We live on flat pieces on top of the Earth	-	Other	-	Space

Table 13 (Continued)

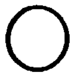
Subjects	What is the shape of the Earth? (Q1)	Which way do we look to see the Earth? (Q3)	Draw a picture of the Earth. (Q11)	Now draw the moon, the stars and the sky. (Q12)	Show me where the people live on the earth. (Q13)	Expl. of flat/sphere conflict (Q14)	Is there an end/edge to the earth? (Q15/16)	Can you fall off that end? (Q17/18)	Where is C-U and where is China? (Q19)	What is down here below the Earth? (Q20)
34	Round	Backwards Forwards				Round like a pancake	No end/edge because Earth is round	Not applicable	*	Sky
38	Round	Sideways					No end/edge	*	*	Solar objects

Table 14

Frequency of Earth Shape Concepts as a Function of Grade

Earth Shape Concepts	Grade 1	Grade 3	Grade 5	Total
1. Sphere	2	8	10	20
2. Questionable sphere	1	3	6	10
3. Inside the sphere	2	4	4	10
4. Disc	0	1	0	1
5. Dual earth	7	2	0	9
6. Rectangle	1	0	0	1
7. Mixed	7	2	0	9
Total	[illegible]	20	20	60

Table 15

Frequency of Responses to the Questions, "Does anyone live here at the bottom of the Earth?" (20a), "Can this man live here at the bottom of the Earth" (20ba) (see figure) and "Why wouldn't he fall?" (20ba)

	Responses	Grade 1	3	5	Total
1.	Yes, people can live at the bottom of the earth. This man can live there. He wouldn't fall because of gravity.	2	5	8	15
2.	Yes, people can live at the bottom of the earth. This man can live there and he wouldn't fall. No explanation.	2	4	2	8
3.	No, people cannot live at the bottom of the earth because it's cold, there is an ocean, etc. But if they did they wouldn't fall. This man would not fall.	1	5	5	11
4.	Yes, people live at the bottom of the earth but this man would not because he is upside down.	5	5	4	14
5.	No, people cannot live at the bottom of the earth because they would fall. This man would fall.	6	1	0	7
6.	Other or Missing.	4	0	1	5
Total		20	20	20	60

Table 16

Freque' cy of Responses to the Question 20bc, "If this person had a ball in his hand and dr ɔpped it, where ᵛwould the ball go? Draw the direction of the ball."

Responses	Grade 1	3	5	Total
1. Toward Earth (correct gravitiy)	4	12	11	27
2. It would float around in space	1	1	3	5
3. Toward Earth, but Earth is flat line under circle	0	0	1	1
4. Away from earth (up/down gravity)	13	7	5	25
5. Ground	2	0	0	2
Total	20	20	20	60

Table 17

Gravity Concepts

Concepts	Questions 20a, 20bb	Question 20bc
1. Correct gravity	People can live at the bottom of Earth. The man would not fall down.	The ball would fall toward Earth
2. Gravity inside the earth	Yes people could live at the bottom of the sphere, but this man would fall or float in space because he is upside down.	Ball would fall away from the Earth
3. Mixed gravity	People can live at the bottom of the Earth. The man would not fall down.	The ball would fall away from the Earth
4. Naive gravity	People cannot live at the bottom of the Earth. Man would fall down	The ball would fall away from Earth
5. Undetermined	Not sure if the man is on Earth or not. If yes, he wouldn't fall.	Not sure
6. Don't know or missing		

Table 18

Frequency of Responses to Gravity Concepts

Gravity concepts	Grade 1	3	5	Total
1. Correct gravity	4	12	11	27
2. Gravity inside the earth	5	5	4	14
3. Mixed	1	2	4	7
4. Naive gravity	8	1	1	10
5. Undetermined	1	0	0	1
6. Don't know or missing	1	0	0	1
Total	20	20	20	60

Table 19

Relationships Between Earth Shape and Gravity Concepts

Earth Shape concepts	Gravity Concepts				
	Correct gravity	Inside gravity	Mixed gravity	Naive gravity	Undetermined DNK
Sphere	16/20	0	1/20	2/10	1/20
Questionable sphere	6/10	3/10	1/10	0	0
Inside the earth	3/10	3/10	3/10	1/10	0
Disc	0	1/1	0	0	0
Dual earth	0	5/9	0	3/9	1/9
Rectangular earth	0	0	0	1/1	0
Mixed	2/9	2/9	2/9	3/9	0

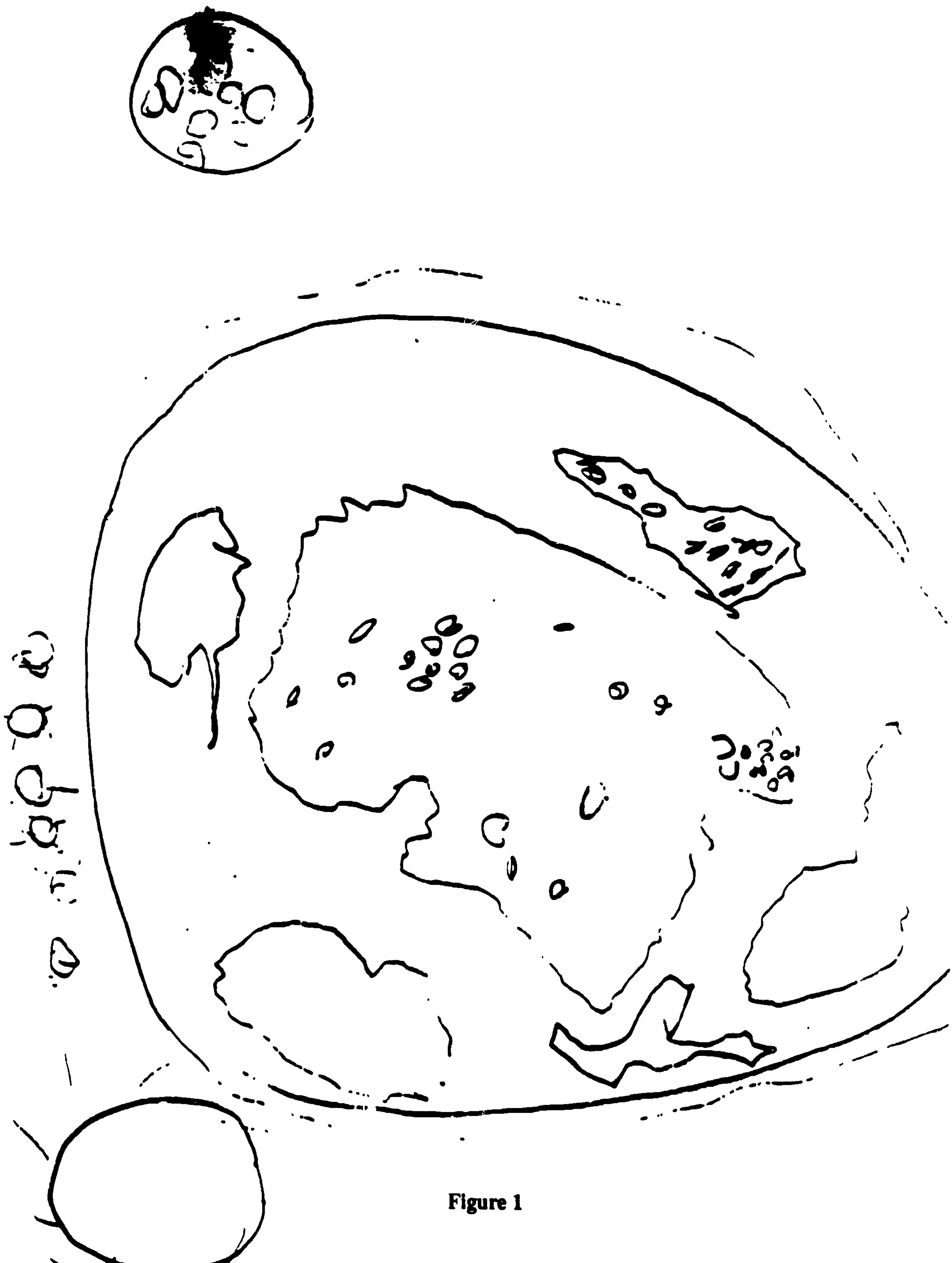


Figure 1

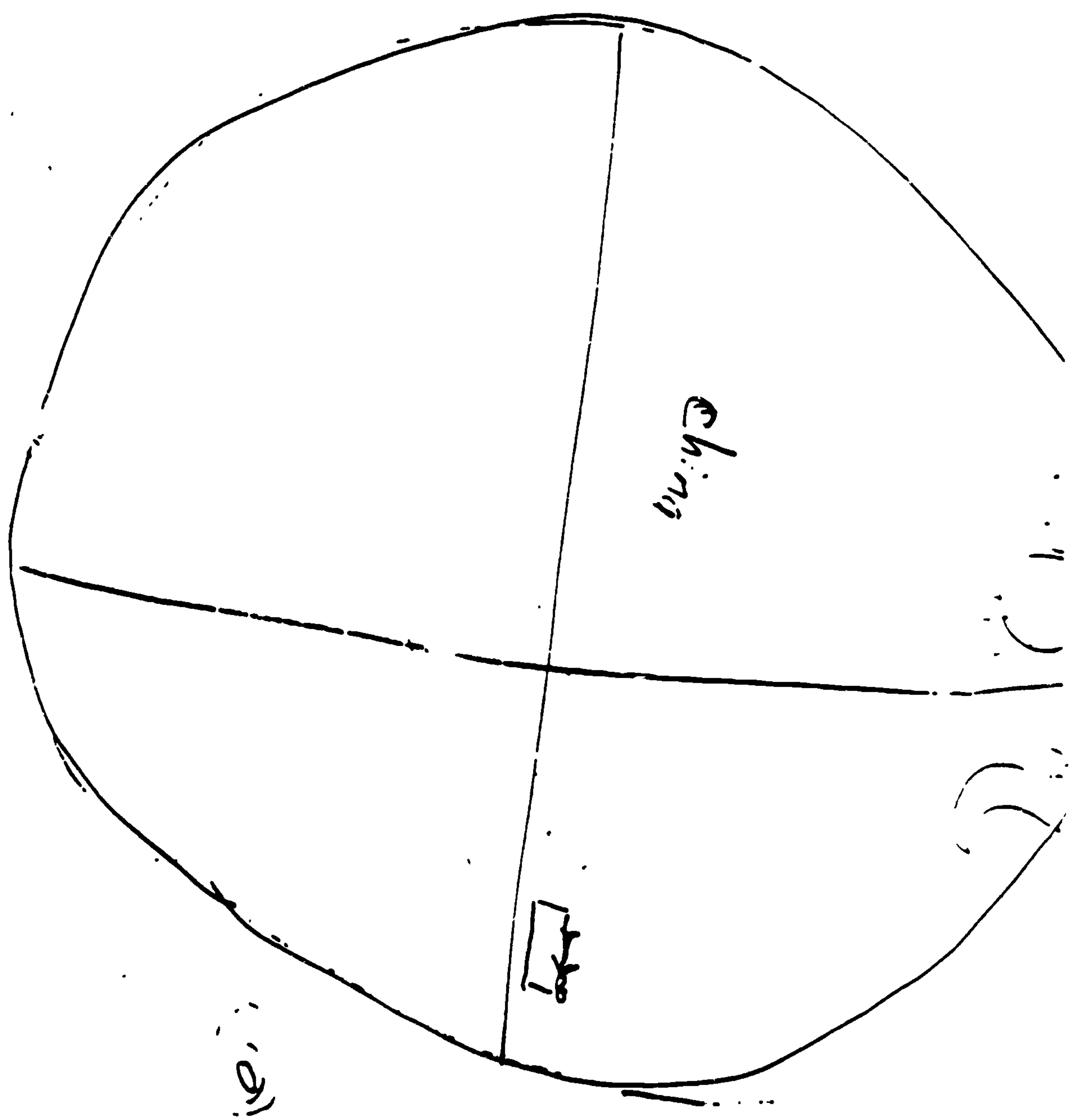


Figure 2

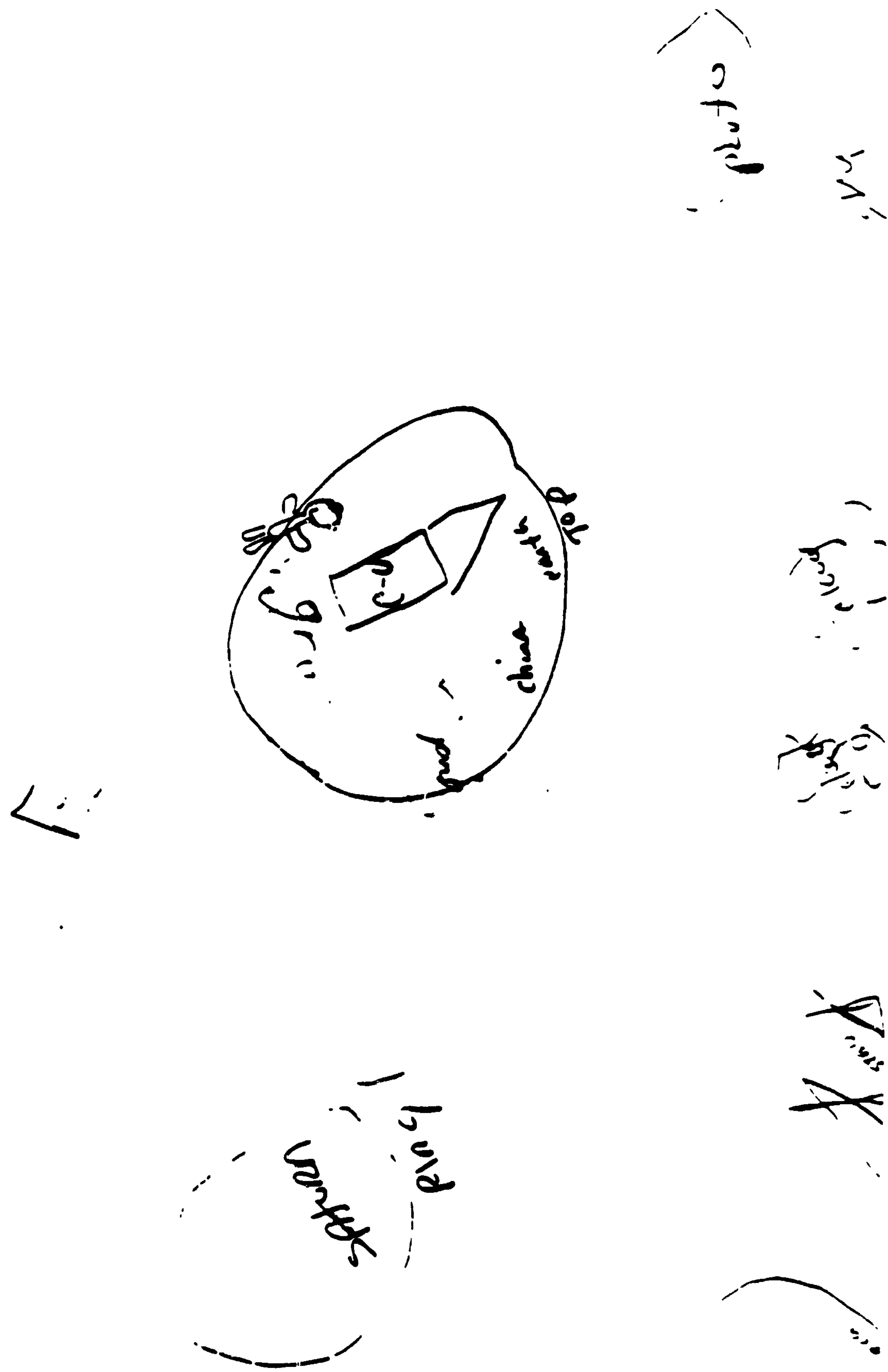


Figure 3

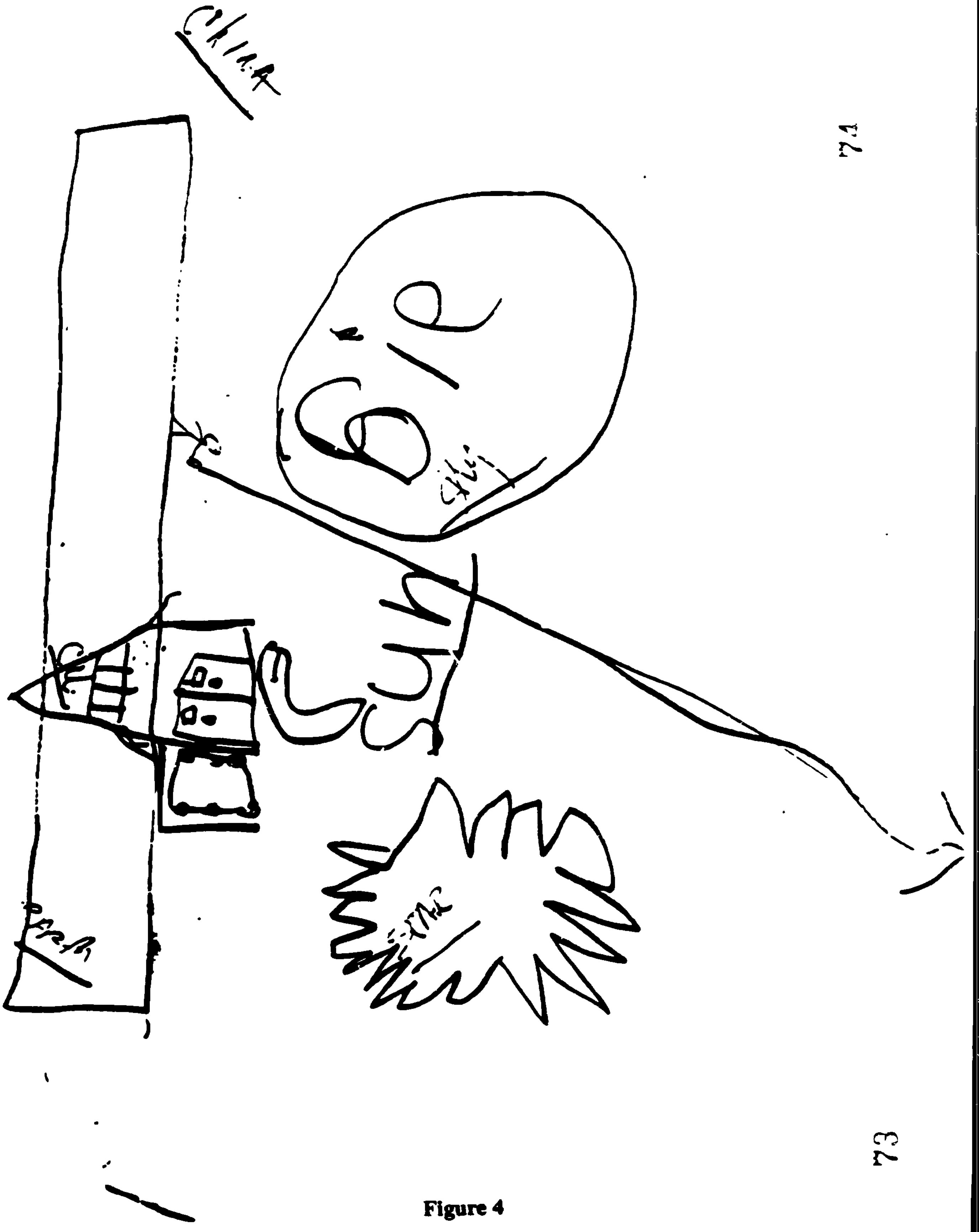


Figure 4

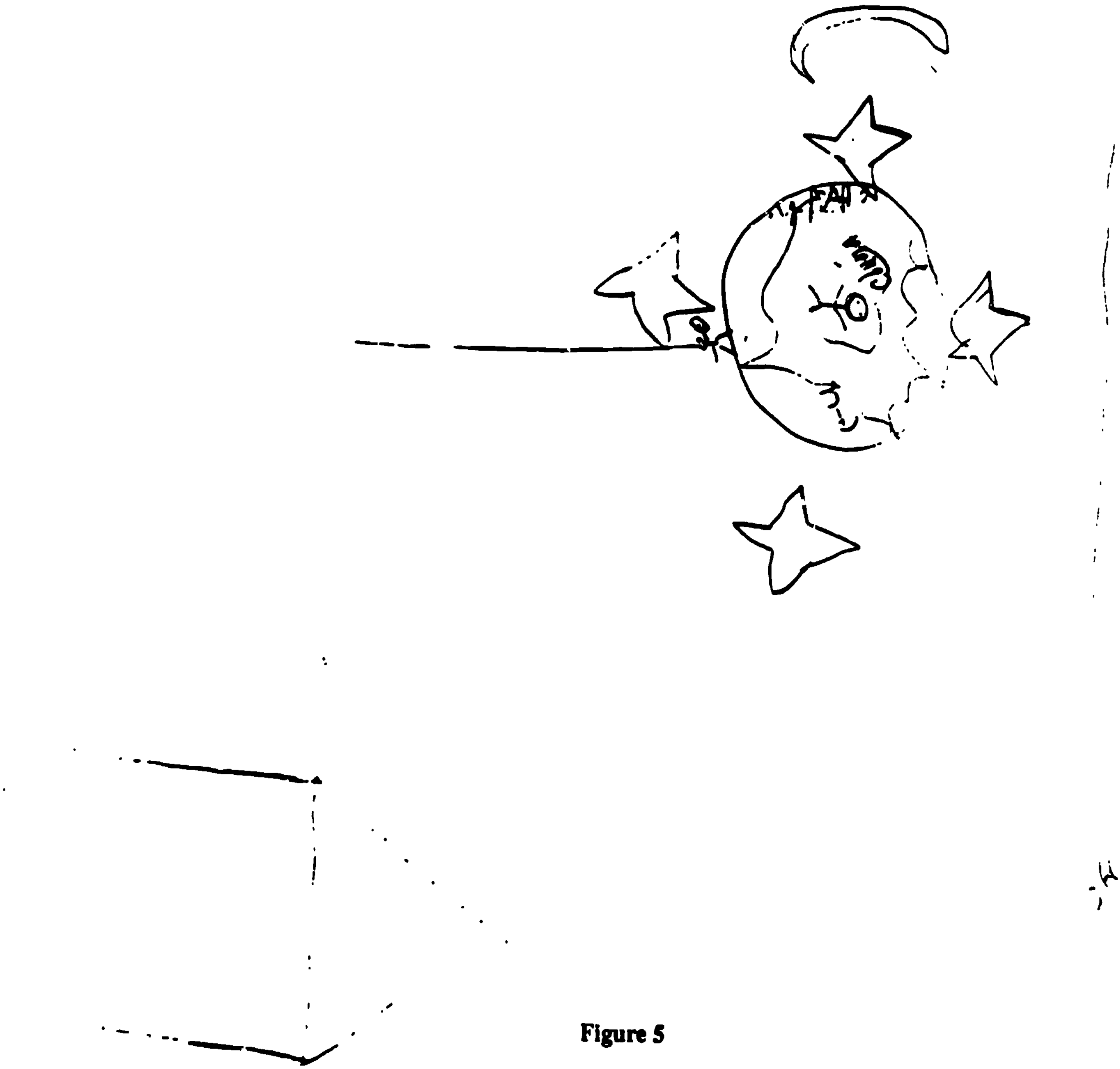


Figure 5